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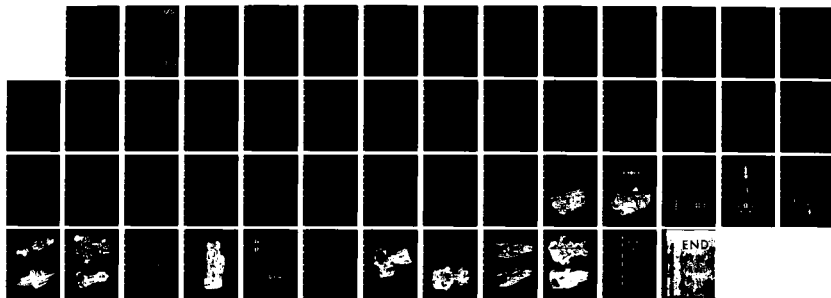
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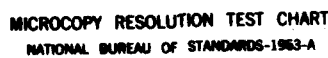
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Washington, D.C. 20591

Study of Noise-Certification Standards for Aircraft Engines

Volume 1: Noise-Control Technology for Turbofan Engines

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June 1983

Final Report

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16. Abstract <p>This study, reported in three volumes, had the purpose of considering the feasibility of establishing an FAA requirement for a manufacturer of aircraft engines to demonstrate compliance with an engine noise-level standard in order to obtain an engine-noise type certificate. The objective of engine-noise type certification (if feasible on the basis of economic reasonableness, technological practicality, and appropriateness to the type design) would be to supplement the aircraft-noise type certification requirements in Part 36 of the Federal Aviation Regulations. The scope of the study was limited to aircraft turbofan engines.</p> <p>Volume 1 identifies sources of noise produced by aircraft turbofan engines, proposes a working definition of an engine's envelope within which an engine manufacturer may incorporate noise-control design features, and evaluates applications of noise-control designs to 22 experimental and production versions of turbofan engines developed over a period from the late 1950s to the mid 1970s and ranging in nominal take-off-rated thrust from 7.2 to 236 kN (1600 to 53 000 lb). A description is included of the general procedure for selecting appropriate noise-control designs applicable within the engine envelope for various sources of engine noise.</p>					
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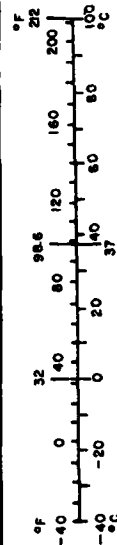
METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
LENGTH				
in	inches	2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
AREA				
in ²	square inches	6.5	square centimeters	cm ²
ft ²	square feet	0.09	square meters	m ²
yd ²	square yards	0.8	square meters	m ²
mi ²	square miles	2.6	square kilometers	km ²
	acres	0.4	hectares	ha
MASS (weight)				
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
VOLUME				
sp	teaspoons	5	milliliters	ml
Tab	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cup	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.96	liters	l
gal	gallons	3.8	liters	l
ft ³	cubic feet	0.03	cubic meters	m ³
yd ³	cubic yards	0.76	cubic meters	m ³
TEMPERATURE (exact)				
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
LENGTH				
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
km	kilometers	0.6	miles	mi
AREA				
cm ²	square centimeters	0.16	square inches	in ²
m ²	square meters	1.2	square yards	yd ²
km ²	square kilometers	0.4	square miles	mi ²
ha	hectares (10,000 m ²)	2.5	acres	ac
MASS (weight)				
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	st
VOLUME				
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m ³	cubic meters	35	cubic feet	ft ³
m ³	cubic meters	1.3	cubic yards	yd ³
TEMPERATURE (exact)				
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



*1 in. = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price \$2.25, SD Catalog No. C13.10.286.

CONTENTS

Section	Page
Introduction	1
Selection of study engines	3
Generally accepted engine envelope	5
Engine design characteristics relevant to noise generation and control	7
Principal sources of engine noise	9
Survey of engine noise-control designs	9
Design features for engine noise control	12
Fan noise	13
Turbine noise	14
Jet noise	15
Combustion noise	15
Concluding remarks	16
References	17

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TABLES

Table	Page
1. Candidate turbofan engines	19
2. Study turbofan engines and their civil-airplane applications (to 1981)	21
3. Turbofan engine noise sources	23
4. Design parameters relevant to turbofan engine noise	25

FIGURES

Figure	Page
1. JT15D-4 from Pratt & Whitney Aircraft of Canada Ltd	28
2. TFE731 from Garrett Turbine Engine Company	29
3. NASA QCGAT (Quiet, Clean General-Aviation Turbofan)	30
4. ATF3-6 from Garrett Turbine Engine Company	31
5. Cutaway view of ATF3-6 installed in a nacelle	33
6. CF700 from General Electric	33
7. ALF-502 from Avco Lycoming	34
8. CF34 from General Electric	34
9. JT3D from Pratt & Whitney Aircraft	35
10. JT8D from Pratt & Whitney Aircraft	37
11. JT8D-209 from Pratt & Whitney Aircraft	37
12. NASA QCSEE (Quiet, Clean, Short-Haul Experimental Engine)	38
13. CFM56 from General Electric and SNECMA	39
14. RB.211-535 from Rolls Royce	40
15. RB.211-22 from Rolls Royce	40
16. CF6-6 from General Electric	41
17. CF6-50 from General Electric	41
18. JT9D-59A,-70A from Pratt & Whitney Aircraft	42
19. Cross-section views of engine installations in wing-engine nacelles on DC-10 airplanes	43

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STUDY OF NOISE-CERTIFICATION STANDARDS FOR AIRCRAFT ENGINES

VOLUME 1: NOISE-CONTROL TECHNOLOGY FOR TURBOFAN ENGINES

INTRODUCTION

In 1968, the Federal Aviation Act of 1958 was amended by Public Law 90-411 to add a Title VI to give the Federal Aviation Administration (FAA) the authority to initiate a regulatory program for control and abatement of aircraft noise and sonic boom. Section 611 of that title required the FAA to consider whether any proposed standard, rule, or regulation is economically reasonable, technologically practicable, and appropriate for the particular type of aircraft, aircraft engine, appliance, or certificate to which it will apply. The Noise Control Act of 1972, in Public Law 92-574, preserved the mandate given to the FAA in 1968, namely to prescribe or amend such standards and regulations as the FAA may find necessary to provide for the control and abatement of aircraft noise in order to afford present and future relief and protection to the public health and welfare.

Standards (or noise-level limits) for the noise that an airplane can make were issued by the FAA in 1969 as a new Part 36 to the Federal Aviation Regulations [1]¹. Federal Aviation Regulations Part 36 (or FAR 36) requires an airplane manufacturer to demonstrate compliance with the applicable noise standard for the effective perceived noise level produced during takeoff and approach at specified locations under, or to the side of, the flight path with the airplane operating at specified conditions. Successful demonstration of compliance with the requirements is necessary for the FAA to issue a type certificate showing that the airplane does satisfy the noise standards.

In 1971, the International Civil Aviation Organization (ICAO) issued an international standard [2] on aircraft noise as Annex 16 to the Convention on International Civil Aviation (Chicago, 1944). Annex 16 may be adopted as a national regulation by any state that is a member of ICAO. The noise-level standards of Annex 16 are similar to those of FAR 36, although the compliance-demonstration requirements differ to some extent.

In the years since adoption of FAR 36 and Annex 16, the manufacturers of engines and airframes have made significant reductions in the magnitude of the noise produced by various classes of new airplanes. Research sponsored by government agencies has effectively supplemented the research sponsored by the manufacturers and led to major improvements in the understanding of the various sources of engine and airplane noise. Government agencies in the United Kingdom and France also made major contributions to the research.

¹Bracketed numbers refer to documents listed in the References Section.

Average noise levels in communities around some airports have been noticeably reduced as a consequence of the introduction of new technology that was the result of the various research efforts, stimulated, in part, by the adoption of type-certification requirements for aircraft noise. On a national, or worldwide, scale, however, the cumulative average noise levels in communities around airports did not decrease significantly in the 1970s because of the relatively large number of older-technology airplanes in the fleet and the general increase in the number of operations.

Continuing reduction in aircraft noise in communities around major airports should occur as a result of the introduction of new airplanes to replace older airplanes that are noisier and also less fuel efficient. Some of the older aircraft will be retrofitted with quieter engines while some will be retired from service under the FAA's retrofit/replacement rule [3]. Achieving a large reduction in the long-term cumulative average noise level in airport communities, however, will require the retirement of most of the older, noisier airplanes.

While the substantial efforts that were made in the 1970s to reduce aircraft noise have produced demonstrable and measureable results, no requirement has ever been promulgated to regulate, by means of a type certificate, the noise produced by an engine, only the noise produced by an airplane, even though section 611 of P.L. 92-574 and its predecessor P.L. 90-411 specifically mention aircraft engines as well as aircraft.

The purpose of the study presented in this report was to consider the feasibility of establishing an FAA requirement for a manufacturer of aircraft engines to demonstrate compliance with an engine noise standard in order to obtain a noise type certificate for an engine.

The objective of engine-noise type certification (if feasible on the grounds of economic reasonableness, technological practicality, and appropriateness to the type design) would be to supplement the aircraft-noise type certification requirements in FAR 36. Other considerations such as takeoff flight procedures, thrust cutbacks, preferential runways, time-of-day scheduling, and land-use planning would continue to be used as much as practical to alleviate noise in airport communities.

It was also considered possible that the implementation of a requirement for an engine-noise type certificate could simplify and perhaps reduce the cost of designing and certifying an airplane.

The study that was conducted is reported in three volumes. Volume 1 examines designs for noise control that can be applied within the generally accepted engine envelope, evaluates the applications of various designs to a wide spectrum of turbofan engines, and describes noise-control design features relevant to the principal sources of engine noise.

Volume 2 describes the results of a survey of capabilities for measuring the noise produced by an engine mounted on an outdoor engine test stand. Recommendations were developed for a standard procedure to conduct static tests to measure engine noise levels and associated engine-performance and meteorological data.

Volume 3 describes the selection of a concept for use as a quantitative measure of engine noise for type-certification purposes. The concept was evaluated against data measured around a large variety of production and experimental engines covering a wide range of engine designs and thrust ratings. Volume 3 also contains a discussion of some of the major issues related to the establishment of a requirement for engine-noise type certification.

SELECTION OF STUDY ENGINES

An objective of the contract was to identify sources of noise associated with aircraft turbofan engines and then to specify technologies to mitigate, attenuate, or eliminate the noise from those sources by application of suitable designs within the generally accepted envelope of the engine itself. A further objective was to identify the extent to which the noise-control technologies have been actually employed in aircraft turbofan engines. To satisfy those objectives it was necessary to select several representative engines from the large array of aircraft turbofan engines that have been, or are being, used in civil-airplane applications. This section describes the selection of the study engines.

The study was limited to turbofan engines because, since the mid 1960s, all new designs for jet-powered airplanes, having a design gross weight greater than 5000 kg (approximately 10 000 lb) and a subsonic design speed during cruise, have employed turbofan engines. Turbofan engines have replaced turbojet engines (an engine design where all the air that enters the engine inlet passes through the compressor and turbine stages and is exhausted from a single nozzle) because the turbofan engine can provide the same cruise thrust with a smaller rate of fuel consumption and also because the turbofan engine generally has a lower jet-exhaust velocity and hence less jet noise at its takeoff-thrust setting than a comparable turbojet engine.

In a turbofan engine, part of the air that enters the engine's air inlet is bypassed around the compressor and turbine stages through a fan-discharge duct. The ratio of the mass-flow rate of air through the fan-discharge duct to the mass-flow rate of gas (air plus fuel) through the turbine-discharge (or core-engine) duct is the bypass ratio.

Generally speaking, the higher the bypass ratio, for a given total thrust, the lower the jet-mixing noise. The fan or bypass airflow may be discharged through a separate fan nozzle or mixed with the core-engine flow and discharged through a single common-flow nozzle. If the bypass airflow is discharged through a separate fan nozzle, the plane of the nozzle exit is located upstream of the plane of the nozzle for the flow from the turbine stages. The distance between the two exit planes can be large (i.e., for a short fan duct) or small (i.e., for a long fan duct where the nozzle exits may be almost coplanar).

A list of candidate turbofan engines was prepared after examining several contemporary sources from the open literature [4 to 8]. Supplemental data sheets that accompany the type certificates for FAA-certified engines were also examined.

The list of 56 engines for which information was obtained is shown in Table 1. The list includes engines that were in production or were under development for future applications. The list also includes experimental engines developed under NASA sponsorship as technology demonstrators for potential advanced airplanes.

Not included on the list are the Rolls Royce Conway engines and the Rolls Royce RB.163 Spey engines. The Conway engine entered service in 1959 and 1960 on Boeing 707 and Douglas DC-8 airplanes. It was the first commercial turbofan engine. However, the bypass ratio was low and the fan and primary flows were exhausted from a single nozzle that operated at a nozzle pressure ratio of the order of 2.5. The jet noise produced during operation at takeoff power was nominally the same as that produced by the JT4A turbojet engines of that era which had comparable thrust ratings and fuel consumption. Conway engines also power the British Aerospace VC-10 airplanes. Conway engines were not included because they were out of production at the time of the study and because their design did not incorporate any significant noise-control technology within the engine.

The Spey engine was not included (even though it was at the time still in production as a commercial engine for some applications such as the Gulfstream American G-II and G-III business/executive jets) because it too was essentially a turbojet engine since it has a low bypass ratio and common-flow exhaust nozzle operated at a nozzle pressure ratio of the order of 2.5 at takeoff. No substantial noise-control technology is incorporated within the engine.

Another turbofan engine that was not included was the CJ805-23 from General Electric. The CJ805-23 was developed in the late 1950s to power the Convair 990, a longer-range version of the earlier Convair 880 that was powered by the CJ805-3 turbojet engine which had been derived from the J79 military turbojet. The CJ805-23 had an aft fan stage as part of a free (i.e., aerodynamically driven) turbine stage. Production of the CJ805-23 ceased early in the 1960s when the 990 program was terminated after 37 airplanes had been manufactured. A mechanically similar engine to the CJ805-23 was, however, included in Table 1, namely the CF700-2D2 for business/executive jets. The CF700 turbofan was developed from the CJ610 turbojet engine that had been derived from the military J85 turbojet engine.

Engines A and C (as they were known), from the NASA/General Electric Quiet Engine Program of the early 1970s, were not included in the list of candidate study engines. As reported in Vol. 3, data from tests of those engines, however, were used in the assessment of the noise-evaluation measure.

The initial selection of 56 candidate study engines was reduced to the list of 22 engines shown in Table 2 along with the various civil-airplane applications for the engines. The engines in Table 2 are listed in order of increasing takeoff-rated thrust. There are eight engines for business/executive jets, eight moderate-thrust engines for transport-category airplanes, and six high-thrust engines for large transport-category airplanes.

The following considerations were involved in reducing the number of candidate engines from the 56 in Table 1 to the 22 in Table 2.

The Williams Research engines (which would have been derivatives of the turbofan engine for cruise missiles) were eliminated because the airplanes for which they were proposed in the late 1970s were either postponed or had their design changed to incorporate a different engine.

The proposed RB.401 engine was eliminated because its development program was delayed and no firm engine-design details were available.

The M45H engine was dropped because the VFW-614 airplane for which it was the powerplant was canceled after completing the production of 16 airplanes. That airplane was the only application for the M45H and production of the engine was discontinued after cancellation of airplane production.

The engines that were ultimately selected were chosen partly to illustrate trends that have occurred in the application of noise-control technology (or potential application for the NASA QCGAT and NASA QCSEE engines). All engines were in actual service (except for the experimental engines) at the time of the study and were considered to represent a 20-year development of turbofan engines as well as noise control.

The QCGAT acronym stands for Quiet, Clean, General-Aviation Turbofan; QCSEE stands for Quiet, Clean, Short-Haul Experimental Engine. UTW means under-the-wing, OTW means over-the-wing, for lower, or upper, surface blown flaps, respectively.

The JT10D from P&WA (item 56 in Table 1) was eliminated as a study engine even though it was under active development because its production configuration was not established at the time of the study. The JT10D did, however, evolve into the PW2037 engine that was chosen by some airlines as the powerplant for the Boeing 757 airplane.

For similar reasons, the CF6-45 and CF6-80 derivative engines were not included though the CF6-45 powers the DC-10-15 and the CF6-80 powers some versions of the Boeing 767 and the Airbus A310.

Engines studied by General Electric and by P&WA for NASA under the Energy Efficient Engine (or E³) program were considered but not included because design details were not established at the time. Information on the design and performance of those engines is available, however, in contractor reports [9, 10].

GENERALLY ACCEPTED ENGINE ENVELOPE

Definition of an engine's envelope for noise-control purposes is important for specification of the configuration of the engine during a noise test with the engine mounted on an outdoor test stand. The definition is also an important consideration in an overall assessment of the feasibility of engine-noise type certification. The boundary around the engine defined by the envelope should be specified in such a way that the definition is equally applicable to all engine manufacturers.

A suitable definition for an engine envelope for noise-control purposes was developed after reviewing engine-design information available in the literature and considering the issues affected by the choice of the definition.

One consideration was that there was a great variety of designs for aircraft turbofan engines. There were also large differences in how the different engines were installed on the various types of turbofan-powered civil airplanes.

Another, and major, consideration was that many engine manufacturers guarantee to the airframe manufacturers that their engine, *as installed*, will permit the *airplane* to comply with the type certification requirements of FAR 36.

Since the objective of incorporating noise-control designs is to permit an airplane to meet applicable type-certification requirements, for engine noise-control purposes the most-efficient design is one that accounts for the noise reduction provided by acoustically absorptive duct linings, special nozzles, and airframe shielding in addition to the noise reduction that can be provided by optimum selection of various internal engine-design parameters.

As noted in more detail in the final section of this report, selection of engine noise-control designs to be applied within an engine's envelope is thus a complex process. An engine manufacturer's evaluation of noise-control designs to incorporate within an engine depends on whether the engine in question is a new or derivative design, on installation effects associated with a particular airplane, and on the business arrangements between the engine manufacturer and the airframe manufacturer. Design responsibility (and technical or business risk) may also be shared with a nacelle or pod manufacturer.

The same engine may also be installed in different ways on different airplanes (e.g., the JT8D is fuselage-mounted on McDonnell Douglas DC-9 airplanes, side fuselage and center-fuselage mounted on Boeing 727s, and pylon-mounted under the wing of Boeing 737 and Dassault-Breguet Mercure airplanes). Hence features that affect noise external to the engine are not the same for all possible installations of an engine.

For the purposes of specifying engine-noise-control technologies as well as the configuration of an engine during a noise-compliance demonstration test, the engine envelope was defined as extending from the engine manufacturer's most-forward air-inlet mounting flange to the engine manufacturer's aft mounting flange on the fan-discharge duct or to the manufacturer's aft mounting flange on the discharge duct from the low-pressure turbine, whichever is farthest aft.

The definition of an engine envelope includes the fan stage(s), compressor stages, combustor stage, and turbine stages. The definition excludes the inlet and discharge ducts upstream or downstream of the flanges except for those ducts considered by the manufacturer to be an integral part of every engine of a given type. The definition includes special internal mixing nozzles on the turbine-discharge duct if they are included as part of a long-duct common-flow exhaust system. The definition excludes external mixing nozzles that might be employed to reduce jet noise at high engine power settings by promoting more-rapid mixing of the exhaust gas with the surrounding air.

If not counted as engine hardware, the definition excludes the aerodynamic fairings around the shaft hubs at the front and rear of the engine. The definition also excludes struts, vanes, doors, or other objects that might be part of the inlet or discharge ducts upstream or downstream of the applicable flanges for a specific airplane installation. The definition includes various structural components or engine accessories that could influence the noise produced

by some component of the engine, for example, fan-case mounting struts, fairings in the fan-discharge duct around engine-support structure or compressor-bleed ducts and around a takeoff shaft that supplies mechanical power to operate an electrical generator and hydraulic pump(s).

The above-described definition for an engine's envelope can be applied equally well for engine noise-control purposes to the wide range of design concepts encompassed by the 22 study engines in Table 2.

ENGINE DESIGN CHARACTERISTICS RELEVANT TO NOISE GENERATION AND CONTROL

Since 1960, the design of aircraft turbofan engines has become increasingly complex as a result of competitive forces to develop high-performance engines having minimal mission fuel burned, a high thrust-to-weight ratio, minimal installed drag, high durability, easy and low-cost maintenance, and other design features, as well as noise levels low enough to insure that an airplane on which the engines are installed meets FAR 36 requirements.

To help envision the complexity of the design of an aircraft turbofan engine and to assist in determining the extent to which noise-control technology was incorporated within an engine's envelope, several cross-section and cutaway drawings were collected and are presented here in Figs. 1 to 19. The cross-section views in Fig. 19 illustrate the use of acoustically absorptive linings on the walls of inlet, fan-discharge, and turbine-discharge ducts to complement noise-control design features incorporated within the engine.

It was apparent from the drawings in Figs. 1 to 19, and a review of engine characteristics given in Refs. 4 to 8, that, although there were many design similarities, there were many differences which could have a significant effect on the level of noise produced by an engine and hence on how much, and what kind of, noise-control considerations were appropriate for the engine.

Most engines are axial-flow designs with the fan stage(s) at the front of the engine where it serves as the first stage(s) for the low-pressure compressor. The CF700, however, has an aft-fan arrangement, see Fig. 6.

The airflow path through the ATF3-6, Figs. 4 and 5, is unique in that the heated, compressed air flows *forward* through the turbine stages after making three 180° turns around the combustor stage before making a final 180° turn and being exhausted through eight outlets located at 45° intervals around the engine within the fan-discharge duct as shown by the typical installation in Fig. 5.

All the lower-thrust engines for business/executive jets (except the CF700 and CF34) use a centrifugal compressor as the high-pressure compressor stage upstream of the combustor stage. The centrifugal compressor is used in combination with a reverse-flow combustor around which there are two 180° flow-path reversals so that the heated air is discharged in the conventional *aft* direction through downstream turbine stages. The use of a centrifugal compressor and a reverse-flow combustor minimizes the length and weight of the engine. The CF700 and the CF34 use axial-flow compressor stages throughout, as do the larger, higher-thrust engines.

On most engines, the fan stage(s) is mounted on the same shaft as the low-pressure compressor stages and the low-pressure turbine stages. In that direct-drive arrangement, the fan rotational speed is the same as the rotational speed of the low-pressure turbine.

For the smaller engines, however, a direct-drive arrangement may not be practical because of the high rotational speed of the small-diameter turbine stages. The smaller engines, therefore, tend to drive the fan through a set of reduction gears, see Figs. 2, 3, 4, and 7. The use of reduction gears reduces the fan tip speed and thus helps to minimize noise from the fan.

Note, however, that the JT15D, see Fig. 1, has a direct-drive fan. The high shaft speed of the fan on the JT15D means that the fundamental blade-passage frequency is greater than 7000 Hz at takeoff power. The CF700, Fig. 6, with its aerodynamically coupled free turbine on which the aft fan is mounted, also has a relatively high rotational speed. The high speed in combination with a large number of fan blades yields a fundamental blade-passage frequency that is greater than 7000 Hz at takeoff power. Atmospheric absorption along the propagation paths from the airplane to an observer on the ground reduces the sound pressure level of the discrete-frequency components of the fan noise at those frequencies to such an extent that the contribution from those components may not be a significant part of the total perceived noisiness of the sound from the airplane.

The two QCSEE engines, Fig. 12, also drive the fan stage through reduction gears even though those engines are relatively high-thrust engines. For those two experimental engines, the reduction gears were included as a design feature to ensure that the fan tip Mach number was subsonic, or barely supersonic, at the takeoff power setting [11, 12].

The rotating components of most of the turbofan engines in Table 2 are mounted on two concentric shafts. In the conventional two-shaft design, one shaft carries the low-pressure turbines that provide the power to drive the fan and the low-pressure compressor stages while the other shaft carries the high-pressure turbines that provide the power to drive the high-pressure compressor stages.

In contrast, the RB.211 series of engines from Rolls Royce has three concentric shafts instead of two. The middle shaft carries an intermediate-pressure turbine to power intermediate-pressure compressor stages. The three-shaft design results in an engine that is somewhat shorter than comparable engines with two concentric shafts, compare Fig. 15 with Figs. 16 to 18.

The ATF3-6 engine is also a three-shaft engine, but not in a three-concentric-shaft arrangement, see Fig. 4. The forward part of the engine contains two concentric shafts, one with the low-pressure turbine and low-pressure compressor stages and one with the fan and the fan-drive turbines. The high-pressure turbine and high-pressure compressor (centrifugal) are located on a separate shaft at the rear of the engine.

PRINCIPAL SOURCES OF ENGINE NOISE

A rich literature has developed since the 1960s with reports of a large variety of engineering studies related to the generation and suppression of noise produced by turbofan engines. On the basis of information in the literature and other experience, the principal sources of noise from aircraft turbofan engines are considered to be those listed under the four major categories in Table 3.

Sound produced during operations at high engine power settings (i.e., sound that contributes most of the area enclosed by a contour of noise at ground level when an airplane takes off and lands) may have contributions from all sources described in Table 3.

Sound characterized in Table 3(d) as crackle is not usually noticeable from airplanes powered by turbofan engines that have bypass ratios greater than 2. It may be noticeable from airplanes powered by low-bypass-ratio engines such as the JT8D-15 and JT8D-17 that operate at higher nozzle pressure ratios but do not have internal mixer nozzles on the turbine exhaust duct. The crackle sound, while noticeable from some engines, does not contribute significantly to effective perceived noise levels.

At low engine power settings, such as those used during landing approach, jet-mixing noise, Table 3(b), often contributes less to the total noise level than the sources of turbomachinery noise and the internal or core-engine noise sources.

While it was not feasible to determine a detailed rank ordering of the various noise sources for the study engines, it is reasonable to expect that turbomachinery noise sources will tend to be dominant on engines having bypass ratios of 4 or greater, especially at landing-approach power settings. Non-engine or airframe noise sources may also be important at approach power settings.

The next section discusses designs available to an engine manufacturer for noise-control technology that could be applied within an engine's envelope. Relevant engine-noise-control design parameters are summarized for the 22 study engines.

SURVEY OF ENGINE NOISE-CONTROL DESIGNS

For the 22 study engines, information related to noise-control designs was collected and is summarized in Table 4. Conditions for the design parameters are noted at the head of Table 4(a). Units for dimensional quantities are given in the metric system. Thrust, for example, is in kilonewtons. (To convert to pounds force from kilonewtons, a conversion factor of 224.8 lb/kN may be used.)

Information in Table 4 is presented in three parts: (1) for the eight engines designed for business or executive jets, (2) for the eight moderate-thrust engines designed for civil jet transports, and (3) for the six high-thrust

engines designed for large civil jet transports. Takeoff-rated thrust ranged from 7.2 kN to 236 kN (1600 lb to 53 000 lb).

The quantities listed in Table 4 illustrate design choices relative to fan noise, turbine noise, and jet noise. Data pertinent to combustion noise, Table 3(c)(1), were not available. Progressive changes that have occurred over the 15 to 20-year span represented by the data in Table 4 may be observed by correlation with the date the engine was certified, or was delivered for the NASA QCGAT and QCSEE engines.

To make significant reductions in the level of jet-mixing noise at takeoff power settings requires the use of lower jet velocities. Increasing the bypass ratio generally reduces the level of jet-mixing noise because the pressure and temperature, and hence velocity, of the turbine-discharge flow are reduced as a consequence of the large amount of power extracted from the flow by the turbine stages to drive the compressor and fan stages.

Axial or circumferential distortions in the airflow into the fan interact with the pressure field on the rotor blades and may increase the level of fan noise. During flight or static operations, mechanical devices in the flow path (e.g., inlet guide vanes or blow-in doors) can be sources of flow distortion. During static testing, additional airflow distortion may be caused by turbulence in the air, from a ground vortex, or from vortices associated with air flowing around structural components of the test stand. The design of the flight inlet duct and the installation of the engine on the airplane should avoid, or minimize the influence of, aerodynamic or mechanical sources of distortion in the inlet airflow. Table 4 tabulates whether an engine has inlet guide vanes and, if it does, what is the axial spacing between the inlet guide vanes and the fan rotor blades.

Based on past experience (and for a given fan pressure ratio), a single-stage fan is preferred over a two-stage fan to avoid the noise caused by interactions between the pressure fields associated with the rotor blades and stator vanes of the two stages. All engines in Table 4, except the older-design JT3D and JT8D engines, had a single-stage fan. The JT8D-209 is a re-fanned version of the JT8D and has a single-stage fan; it also has inlet guide vanes but they are located well upstream of the fan.

The tip speed of the fan blades and the pressure rise across the fan are parameters that are related to the noise produced by the fan rotor stage.

If the tip Mach number of the fan rotor blades is subsonic, multiple-pure-tone or buzzsaw noise will not be present. However, for the same total thrust, an engine designed to have a subsonic fan-blade tip Mach number at the takeoff power setting may have more stages, weigh more, and cost more to buy and maintain than an engine designed to operate with a supersonic fan-blade tip Mach number at takeoff power. Moreover, buzzsaw sounds can be significantly attenuated by installation of special linings on the wall of the inlet duct. Furthermore, buzzsaw sounds, if present, usually do not contribute significantly to an airplane's effective perceived noise level, though they may be noticeable inside the passenger compartment during takeoff and climbout.

The ratio of the number of vanes in the fan outlet stator stage to the number of blades in the fan rotor stage is an important parameter in designing an engine

so that forward-propagating and rearward-propagating interaction modes will decay inside the inlet or fan-discharge duct within a short distance from the rotor blades.

Use of an optimum ratio for vane count to blade count to promote rapid decay of interaction modes is applicable for subsonic fan tip speeds such as would normally exist at landing-approach power settings. Theory to guide the selection of the optimum ratio of vane count to blade count is well established in the technical literature. The theory would usually be applied to spectral components of fan noise in the 2000 to 5000-Hz range so as to minimize the perceived noisiness of sounds in the frequency region of greatest human sensitivity. Table 4 shows that the ratio is of the order of 2 to 2.5 for the newer-designed engines, with as much as 3.67 for the Garrett TFE731 engine.

Increasing the axial spacing between rotor and stator stages reduces turbomachinery noise by reducing interactions between an upstream or downstream stage and the rotating pressure field associated with a rotor stage. Table 4 shows that axial spacings between fan rotor blades and fan outlet guide vanes are significantly greater for the newer-design engines than for the older-design engines.

The frequency of rotor blade passing is of interest because it is desirable to avoid discrete spectral components in the 2000 to 5000-Hz range, especially at landing-approach power settings. Spectral components at frequencies greater than 5000 Hz are rapidly attenuated by atmospheric absorption.

Acoustically absorptive linings on surfaces within the engine's envelope can be an important element of an engine's total noise-control design. Table 4 shows that the newer-design moderate- and high-thrust engines have absorptive duct linings on at least some surfaces within the engine envelope. Except for the TFE731, none of the engines for business/executive jets had absorptive duct linings within the engine envelope.

Because the data in Table 4 apply to actual engines, the data represent designs that were considered to be technologically practicable and appropriate to the engine type as of the date the design was established. No data could be located in published reports on the costs of developing, manufacturing, operating, and maintaining the noise-control features. Thus, no data were available to estimate the economic reasonableness of the nonrecurring or recurring costs allocable to the incorporation of noise-control features within a turbofan engine.

Economic data that were available, e.g., Ref. 13, were mainly applicable to the costs associated with developing acoustically absorptive inlets and exhaust ducts to reduce fan and turbine noise from JT3D-powered airplanes, or with developing external mixing nozzles to reduce jet noise from JT8D-powered airplanes. Such data were outdated as well as irrelevant for the purpose of this study.

DESIGN FEATURES FOR ENGINE NOISE CONTROL

During the time when an engine manufacturer is designing and developing a new or derivative turbofan engine for application on a civil airplane, estimates are made for the far-field sound pressure levels produced by the various sources of engine noise, internal and external. The estimates are made for various engine power settings including takeoff and landing approach and are applicable to a particular engine configuration as well as particular inlets and exhaust ducts.

Normally, noise levels from the various sources of engine noise are estimated for an engine operating under static conditions on an outdoor test stand. Those static noise-level estimates are then projected, by proprietary methods, to flight conditions. Installation effects, for particular airplane applications, are also taken into account. Installation effects can reduce noise (by shielding) or increase noise (by reflection or interaction with exhaust flows). The flight conditions would usually include the takeoff and approach conditions of FAR Part 36 and ICAO Annex 16 as well as special requirements of a particular customer. Estimates of airplane noise levels would also include an estimate of the contribution from non-engine (i.e., airplane) noise sources.

The result of the estimates is the identification of those sources of engine noise that need additional consideration to ensure that the engine meets any guaranteed noise levels and that the airplane on which it is installed is also able to meet its requirements for noise type certification.

The estimates of the relative contributions of the various noise sources, at the various engine power settings, are then utilized to refine the engine's design through modifications of its aerodynamic, thermodynamic, or structural arrangements. Selection of specific noise-control design features often requires tradeoff studies to evaluate the impact of the adoption of various design options on parameters such as thrust, fuel consumption, cruise drag, engine weight, maintainability, installation requirements, nonrecurring and recurring costs, and engine development schedule. Allowance is included for thrust increases in derivative versions of the basic engine as well as tolerances on the accuracy of the estimates of engine noise levels.

Noise-control design features described below have been employed to various degrees in previous or existing engines. The list is not necessarily complete. Also, the items that are listed may not all be applicable or appropriate for a specific engine. The list, however, does represent design features that a manufacturer of civil turbofan engines would likely consider for those noise sources deemed to require noise control to meet prescribed requirements. The list of noise-control design features is not intended to serve as a checklist of items to be included as part of an engine-noise type-certification requirement.

For any particular engine, the ease of incorporating the various noise-control design features listed below depends to a large extent on whether the application is for a new or an existing engine design. For a new-design engine, there are more opportunities to modify basic elements within the engine's envelope than for an existing-design engine or a derivative of an existing-design engine.

The list of noise-control design features includes items related to fan noise, turbine noise, jet noise, and combustion noise. The items were limited to those that could be incorporated within the engine's envelope. Guidance as to appropriate numerical values for specific items (e.g., axial spacings, vane-count to blade-count ratios, and jet-exhaust velocities) may be obtained from the data given in Table 4.

Sound-absorbing linings that might be installed on surfaces in the inlet, fan-discharge, and turbine-discharge ducts outside the engine's envelope are not included as part of the list of design features even though they may be an important element in the total noise-control design that permits an airplane on which the engine is installed to comply with the noise-level standards of FAR Part 36 or ICAO Annex 16. Also, the list does not include such items as external mixer nozzles, special convergent-divergent nozzles, variable-area inlets, or variable-area fan nozzles although such items may also be part of a total design for controlling an airplane's noise level during takeoff and landing approach.

FAN NOISE

For fan noise, the principal requirement for noise control is usually the need to minimize the perceived noisiness caused by discrete spectral components in the frequency region of maximum human sensitivity to noise, i.e., generally from 2000 to 5000 Hz. For most turbofan engines, it is also generally true that, to meet the flyover noise standards of FAR 36, more fan-noise suppression is needed at landing-approach power settings than at takeoff or climbout power settings.

Control of fan noise may include the following design features:

- minimize the generation of fan noise caused by interactions between the rotating pressure field on the fan blades and nonuniform pressure fields upstream and downstream of the fan, for example, by:
 - using a single-stage fan
 - eliminating sources of nonuniform axial or circumferential distortion in the airflow into the fan, for example, by eliminating objects such as inlet guide vanes or front-bearing support struts
 - using axial spacings as large as practical between the fan blades and objects upstream or downstream of the fan blades [(1) greater axial spacing may be required between the fan blades and downstream objects in the fan-discharge duct than between the fan blades and downstream objects in the flow path into the low-pressure compressor, (2) objects in the fan-discharge duct include fan outlet guide vanes, support struts, components of a fan thrust reverser, compressor bleed ducts, a shaft for extracting mechanical power, a fuel-supply pipe, and conduits carrying electrical leads for controls and instruments]

- minimize the strength of the pressure fluctuations on the fan blades through selection of engine cycle parameters, fan diameter, and fan rotational speed so as to minimize, for example, fan-blade tip-section pressure rise and fan-blade tip speed
- through choice of the number of fan blades and the number of fan outlet guide vanes in the fan-discharge duct (for a single-stage fan), select a ratio of vane count to blade count so that at subsonic tip Mach numbers (i.e., at approach power settings) modes for sound caused by interaction effects are "cut off" and decay within a short distance forward and aft of the fan blades [note: for frequency components in the 2000 to 5000 Hz range, the cut-off criterion for some engine designs may apply to the second harmonic rather than the fundamental blade-passage frequency and thus require a greater vane-count to blade-count ratio to ensure cut off of interaction modes at those frequencies]
- use shrouds at the tips of the fan blades rather than mid-span shrouds to minimize the generation of broadband noise
- for fan blades without tip shrouds, minimize the clearance at the tips of the blades
- install sound-absorbing linings on as many surfaces and over as much surface area as practical along the walls of the airflow passages in the engine's fan case (or fan frame) and in the fan-discharge duct if it is within the engine envelope

TURBINE NOISE

If the contribution of turbine noise is indicated by the estimates of noise-source strength to require suppression, then, as for fan noise, the greatest need for turbine noise control will usually be for the discrete spectral components at landing-approach power settings. However, the low-pressure turbine may have several stages and the relative contribution of turbine noise from each stage should be estimated to optimize the design for turbine noise control.

Control of turbine noise involves many of the design features applicable to control of fan noise.

- minimize the influence of interaction mechanisms between pressure fields associated with rotating and stationary components of the low-pressure turbine stages by making use of relatively large axial spacings
- promote the rapid decay of downstream-propagating interaction modes by selection of the proper ratio of vane count to blade count for frequency components in the region of concern for those stages operating with subsonic tip Mach numbers (at the local speed of sound) at approach power settings
- favor designs for turbine stages having a large number of turbine blades so that the fundamental blade-passage frequency at approach power settings is as high as possible, preferably greater than 5000 Hz

- install sound-absorbing linings on the walls of the turbine-discharge duct

JET NOISE

Jet noise will often be a major source of noise at takeoff and climbout power settings; it is usually less important than other noise sources at approach power settings. Noise-control design features within the engine envelope include:

- bypass ratios as large as feasible
- exhaust gas temperatures and exhaust gas pressures that are as low as feasible so as to minimize the velocity of the jets from separate-flow engines or the single jet from mixed common-flow engines
- for an engine designed to be operated in a long-duct nacelle with one common-flow external nozzle, a mechanical, internal mixer nozzle on the turbine-discharge duct may provide more-complete thermal mixing of the hot turbine exhaust with the cooler fan exhaust in a shorter length than a comparable round nozzle, as well as provide some noise reduction depending on the engine's aerothermodynamic design

COMBUSTION NOISE

If the combustion process is indicated to be an important noise source, research sponsored by the FAA and NASA has indicated that the following considerations should help minimize the combustion noise that propagates through the turbine stages and out the turbine-exhaust nozzle, see the summary in Ref. 14.

- choose a combustor design that minimizes unsteadiness in the heat-release rate within the turbulent combustion zone and thereby minimize fluctuations in the density and pressure of the burning gas
- for a given combustor design, use as many fuel injectors as practical to minimize the volume of coherent pressure fluctuations
- use mechanical or aerodynamic means to mix, as thoroughly as possible, the flow from the discharge of the high-pressure compressor with the fuel injected into the combustor to achieve a stable flame with minimum unsteadiness

CONCLUDING REMARKS

Technology available to an engine manufacturer for controlling the noise produced by aircraft turbofan engines was studied by considering the principal sources of engine-generated noise and applicable noise-control measures that could be incorporated within an engine's envelope. For noise-control purposes, an engine's envelope was defined as the boundary around the engine extending from the engine manufacturer's most-forward air-inlet mounting flange to the engine manufacturer's aft mounting flange on the fan-discharge duct or to the manufacturer's aft mounting flange on the discharge duct from the low-pressure turbine, whichever is farthest aft.

To evaluate the application of designs for engine noise control, a selection was made of 22 turbofan engines representing production and experimental engines for applications ranging from business/executive jets to large, wide-body jet transports. The 22 engines had takeoff-rated thrusts ranging from 7.2 kN to 236 kN (1600 lb to 53 000 lb). Engine designs covered FAA certification dates ranging from 1967 to 1982.

A description was given of the general approach that an engine manufacturer might utilize to determine which sources of noise on a particular engine type need noise-control considerations. Design features were discussed that are applicable to control of fan noise, turbine noise, jet noise, and combustion noise. Selection of the specific noise-control design features to incorporate within the engine envelope (or outside the envelope) would be made in conjunction with consideration of other design constraints such as mission fuel burn, take-off thrust, engine weight, engine selling price, airplane installation requirements, durability requirements, and engine development schedule.

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11. D. L. Stimpert, "Quiet Clean Short-Haul Experimental Engine (QCSEE) Under-the-Wing (UTW) Composite Nacelle Test Report, Volume II - Acoustic Performance," National Aeronautics and Space Administration Contractor Report CR-159472 (November 1979).
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13. Rohr Corporation, "Economic Impact of Implementing Acoustically Treated Nacelle and Duct Configurations Applicable to Low Bypass Turbofan Engines," FAA Contractor Report FAA-NO-70-11 (July 1970).

14. Alan H. Marsh and Gary L. Blankenship, "Review of Turbofan-Engine Combustion- and Jet-Noise Research and Related Topics," FAA Contractor Report FAA-RD-80-16 (January 1980).

Table 1. Candidate turbofan engines

Item	Designation	Manufacturer
1	WR19-3	Williams Research Corporation Walled Lake, Michigan
2	WR44-800	
3	JT15D-1,-1A	Pratt & Whitney Aircraft of Canada Pratt & Whitney Aircraft Group Longueuil, Quebec
4	JT15D-4	
5	ALF-502D	Avco Corporation Lycoming Division Stratford, Connecticut
6	ALF-502H	
7	ALF-502L	
8	ALF-502R	
9	NASA QCGAT	
10	TFE731-2	Garrett Turbine Engine Co. [previously AiResearch Manufacturing Company of Arizona] Phoenix, Arizona
11	TFE731-3	
12	TFE731-4	
13	ATF3-6-1	
14	ATF3-6-2	
15	NASA QCGAT	
16	CF700-2D2	General Electric Company Aircraft Engine Group Lynn, Massachusetts
17	CF34	
18	RB.401-07	Rolls Royce Ltd. Bristol Engine Division Bristol, England
19	M45H-01	Rolls Royce-Bristol in collaboration with SNECMA, Paris, France

Table 1. Concluded

Item	Designation	Manufacturer
20	RB.211-22B	Rolls Royce Ltd. Derby Engine Division Derby, England
21	RB.211-524,-524B,-524D	
22	RB.211-535	
23	CF6-6D	General Electric Company Aircraft Engine Group Evendale, Ohio
24	CF6-6D1	
25	CF6-50A	
26	CF6-50C/-50E	
27	CF6-50L	
28	CF6-50M	
29	CF6-50C1/-50E1	
30	CF6-50C2/50E2	
31	CF6-45	
32	CF6-80	
33	NASA QCSEE-UTW	
34	NASA QCSEE-OTW	
35	CFM56-2,-3	General Electric Company and SNECMA as CFM International
36	JT3D-1	Commercial Products Division Pratt & Whitney Aircraft Group East Hartford, Connecticut
37	JT3D-3	
38	JT3D-3B	
39	JT3D-7	
40	JT8D-1,-7	
41	JT8D-9	
42	JT8D-11	
43	JT8D-15	
44	JT8D-17,-17R	
45	JT8D-209	
46	JT8D-217	
47	JT9D-3A	
48	JT9D-7	
49	JT9D-7A	
50	JT9D-7F	
51	JT9D-7Q	
52	JT9D-20	
53	JT9D-59A,-70A	
54	JT9D-59B,-70B	
55	JT9D-59D,-70D	
56	JT10D-4	

Table 2. Study turbofan engines and their civil-airplane applications (to 1981)
(a) low-to-moderate-thrust engines

Item	Manufacturer	Designation	Applications
1	Avco Lycoming	QCGAT-AL	experimental engine for NASA-Lewis for advanced business jets
2	P&WAC	JT15D-4	Citation II; Aerospatiale Corvette; Mitsubishi Diamond I
3	AiResearch ¹	TFE731-3	Jet Star II; Learjet 35/36; Citation III; Falcon 50; BAe 125-700; IAI 1124 Westwind; Sabreliner 65A Learjet 54/55/56
4	AiResearch ¹	QCGAT-A1R (TFE731-5)	experimental engine for NASA-Lewis for advanced business jets
5	General Electric	CF700-2D2	Falcon 20; Sabreliner 75A
6	AiResearch ¹	ATF3-6-2	Falcon 20G; HU-25A Falcon Guardian
7	Avco Lycoming	ALF-502L	Canadair Challenger 600; NASA QSRA; BAe-146
8	General Electric	CF34	Canadair Challenger 601

¹Now the Garrett Turbine Engine Company

Table 2. Concluded

(b) moderate-thrust engines

Item	Manufacturer	Designation	Applications
9	P&WA	JT8D-9	727-100, -100C, -200; 737-200, -200C; DC-9-20, -30, -40
10	P&WA	JT8D-17	727-200; 737-200; DC-9-50
11	P&WA	JT3D-7	707-320C; DC-8-62, -63
12	P&WA	JT8D-209	DC-9-80
13	General Electric	QCSEE-UTW	experimental engine for NASA-Lewis for lower-surface-blown STOL demonstrator
14	General Electric	QCSEE-OTW	experimental engine for NASA-Lewis for upper-surface-blown STOL demonstrator
15	General Electric and SNECMA	CFM56-2	DC-8-71, -73
16	Rolls Royce	RB.211-535	757

(c) high-thrust engines

17	General Electric	CF6-6D	DC-10-10
18	Rolls Royce	RB.211-22B	L-1011-1, -100
19	P&WA	JT9D-7A	747-100; 747SR; 747-200; 747SP
20	Rolls Royce	RB.211-524B	L-1011-500; 747-200; 747SP
21	General Electric	CF6-50C/-50E	747-200; DC-10-30; A300B4
22	P&WA	JT9D-59A, -70A	747-200; DC-10-40; A300B

Table 3. Turbofan engine noise sources

(a) discrete-frequency and broadband noise
from turbomachinery components

- (1) interactions between the blades of a rotating stage and time and spatial inhomogeneities in the velocity of the flow into the blades
- (2) interactions between the blades of a rotating stage and a non-uniform pressure field around engine components downstream of the rotor blades
- (3) periodically fluctuating pressures associated with the pressure rise on each blade of a rotor stage
- (4) interactions between periodic defects in the velocity (or pressure) in the wake of a rotor stage and the vanes of a downstream stator stage, or a downstream rotor stage, or both
- (5) interactions between periodic variations in the intensity of the turbulence in the wake from a rotor stage and the vanes of a downstream stator stage, or rotor stage, or both
- (6) small irregularities in the shape or circumferential spacing of the fan rotor blades that, at moderate-to-high engine power settings when the resultant Mach number of the flow over the blade becomes supersonic, cause the establishment in the fan-inlet duct of a forward-propagating sound field having a line spectrum with a fundamental frequency equal to the fan rotational speed and many harmonics (i.e., multiple-pure-tone or buzzsaw noise)

(b) broadband noise from jet mixing
external to the engine

- (1) for engines having two separate external nozzles for the fan and turbine-discharge exhaust flows, interactions between the hot gas discharged from the turbines, the compressed air discharged from the fan, and the surrounding air
- (2) for engines having one external nozzle on a long-duct, common-flow nacelle, interactions between the flow of exhaust gas and the surrounding air

Table 3. Concluded

(c) broadband noise associated with internal components of an engine (core-engine noise or core noise)

- (1) pressure fluctuations within the combustion chamber(s), caused by turbulence within the flow field in and around the chamber(s) and by fluctuations in the heat-release rate which occur as part of the fuel-burning process, and interactions between those pressure fluctuations and the blades and vanes of downstream turbine stages as the combustion noise propagates out the turbine-discharge duct
- (2) augmentation of broadband jet-mixing noise by disturbances that propagate down the fan-discharge and turbine-discharge ducts. Sources of such disturbances in the exhaust flows include: (a) wakes from struts that support the aft bearing for the low-pressure rotor shaft, (b) wakes from the flow around exhaust-pressure and exhaust-temperature probes, (c) wakes from the flow over (or into and out of) components of the thrust-reverser(s), (d) wakes from the flow around and out of special internal mixing nozzles on the turbine discharge in a long-duct, common-flow nacelle, (e) turbulence in flow that may have separated from the surface of the tailcone fairing over the shaft hub, (f) turbulence in the discharge from turbine stages, especially when the engine is operated at low power settings, (g) periodic fluctuations in the hydrodynamic and acoustic pressures from fan, compressor, and turbine stages, and (h) pressure fluctuations from the combustion chamber(s)
- (3) augmentation of broadband jet-mixing noise by interactions between the turbulence in the jet flow field downstream of the nozzle exit and fluctuations in the static pressure of the jet across the plane of the nozzle (as influenced by the swirling motion of the exhaust) as well as fluctuations in pressure at the lip of each nozzle (as influenced by the flow field in which each nozzle is immersed)

(d) crackle and shock-cell noise as components of jet-exhaust noise

- (1) when the nozzle pressure ratio (ratio of average total pressure within a nozzle to the static pressure in the surrounding ambient air) exceeds the critical pressure ratio (approximately 1.9), then shock waves exist in the jet flow field downstream of the nozzle exit
- (2) for nozzles operated at moderately supercritical pressure ratios (for example, between 1.9 and 2.4, approximately), the sound from the jet exhaust has a character best described by the word crackle
- (3) interactions between shock waves and turbulence in the jet flow field are likely sources of crackle and of other forms of shock-cell noise

Table 4. Design parameters relevant to turbofan engine noise
(a) ENGINES FOR BUSINESS/EXECUTIVE JETS

Conditions: Static operation at sea level. Ambient temperature 15°C. No wind. Takeoff-rated power. No installation losses. Ideal inlet and exhaust ducts with no acoustical treatment in ducts. No compressor bleed or mechanical power extraction except for engine operation and cooling. Ideal exhaust nozzles.

PARAMETER	QCGAT -AL	JT15D-4	TFE/31-3	QCGAT AIR	CF700-2D2	ATF3 -B-2	ALF-502L	CF34
1. General								
Year certified or delivered	1979	1974	1974	1979	1975	1980	1980	1982
Total thrust, kN	7.22	11.12	16.46	17.50	20.02	24.20	33.36	38.48
Total mass flow rate (air + fuel), kg/s	31.2	34.9	52.8	64.3	58.0	74.0	115.2	147.4
Bypass ratio	8.4	2.6	2.7	4.0	2.0	2.7	5.0	6.2
Fan-exit mass flow rate (air), kg/s	27.9	25.2	38.7	51.4	38.7	54.2	96.0	126.9
Core-engine mass flow rate (air + fuel), kg/s	3.3	9.7	14.1	12.9	19.3	19.8	19.2	20.5
2. Inlet Guide Vanes (IGV)								
Inlet guide vanes or support struts?	No	No	No	No	8 struts	No	No	No
Spacing between tip of IGVs (or struts) and fan blades : average fan-blade chord ^a	—	—	—	—	2.90	—	—	—
3. Fan								
Number of fan stages	1	1	1	1	1	1	1	1
Fan diameter, cm	58.17	52.83	70.61	76.96	91.44	76.96	101.09	111.76
Fan rotational speed, rev/min	11,200 ^b	16,000	11,037 ^b	9120 ^b	8670	9858 ^b	7081 ^b	6700
Fan tip speed, m/s	341.1	442.6	408.1	367.5	415.1	397.2	374.8	392.0
Fan-tip-section pressure ratio	1.38	1.54	1.49	1.45	1.60	1.59	1.46	1.45
Number of fan blades	24	30	30	36	54	36	40	28
Number of fan-stator outlet guide vanes	59	66	110	121	57	97	86	60
Ratio of number of fan outlet guide vanes to number of fan blades	2.46	2.36	3.67	3.36	1.06	2.69	2.15	2.14
Spacing between tip of fan outlet vanes and fan blades : average fan-blade chord ^a	2.3	2.33	2.0	5.0	0.47	2.18	4.71	1.21
Spacing between root of fan outlet vanes and fan blades : average fan-blade chord ^a	1.6	2.08	1.6	4.0	0.44	1.58	2.35	0.54
Fan-blade-passagage frequency, Hz	4480	7467	5518	5472	7803	5915	4721	3127
4. Acoustical treatment								
Fan-case (fan-frame) acoustical treatment: (yes or no)	No	No	Yes	No	No	No	No	No
-on outer wall forward of fan rotor blades	No	No	Yes	No	No	No	No	No
-on outer wall between fan rotor blades and outlet guide vanes	No	No	No	No	No	No	No	No
-on inner wall of fan-exhaust duct between fan blades and fan outlet guide vanes	No	No	No	No	No	No	No	No
-on fan-stator outlet guide vanes	No	No	No	No	No	No	No	No
5. Low-Pressure (LP) turbine								
Number of last-stage low-pressure-turbine rotor blades	36	55	56	56	54	55	40	136
Number of last-stage low-pressure-turbine outlet-support struts	c	6	6	6	6	NA	c	4
Ratio of number of outlet support struts to number of last-stage LP turbine blades	c	0.109	0.107	0.107	0.111	NA	c	0.029
Spacing between tip of last LP turbine blades and outlet struts : aver. last LP turbine blade chord ^a	c	2.08	2.8	2.8	1.03	NA	c	3.14
If geared fan, turbine shaft speed, rev/min	31,890	—	18,606	19,380	—	16,508	23,876	—
LP turbine-blade-passagage frequency, Hz	19,134	14,667	17,366	18,088	7803	15,132	15,917	15,187
6. Jet								
Fan-discharge jet velocity, m/s	198 ^d	280	264	274 ^d	270	344 ^e	280	251
Turbine-discharge jet velocity, m/s	—	427	463	—	460	—	445	291

^aSpacing and chord lengths are measured in a plane containing the engine axis and along lines parallel to the engine centerline. Average blade chord is determined by averaging several projected axial chord lengths between the root and the tip of a blade. Spacing between the tip or root of an outlet stator vane and a rotor blade is measured from the projected leading edge of a vane to the projected trailing edge of a blade.

^bGeared fan

^cNo turbine-outlet struts

^dMechanical forced-mixing internal nozzle on the turbine discharge; long fan duct; single common-flow, round, external exhaust nozzle

^eTurbine and fan-discharge flow are mixed and exhausted from a common-flow annular nozzle

Table 4 . Continued
(b) MODERATE-THRUST ENGINES FOR CIVIL JET TRANSPORTS

PARAMETER	JT8D-9	JT8D-17R	JT30-7	JT8D-200	QCSEE -UTW	QCSEE -OTW	CFM56-2	RB.211 -535
1. General								
Year certified or delivered	1967	1974	1967	1980	1978	1978	1979	1982
Total thrust, kN	64.50	77.40	84.52	85.63	77.40	90.3	106.76 ¹	166.36
Total mass flow rate (air + fuel), kg/s	144.7	147.9	214.1	218.2	405.5	405.5	375.1	512.1
Bypass ratio	1.04	1.00	1.43	1.78	12.1	10.1	6.0	4.46
Fan-exit mass flow rate (air), kg/s	73.9	73.95	126.1	139.7	374.6	369.0	321.6	418.3
Core-engine mass flow rate (air + fuel), kg/s	70.8	73.95	88.0	78.5	30.9	36.5	53.5	93.8
2. Inlet Guide Vanes (IGV)								
Inlet guide vanes or support struts?	19 IGV	19 IGV	23 IGV	23 IGV	No	No	No	No
Spacing between tip of IGVs (or struts) and fan blades : average fan-blade chord ^a	1.2	1.2	0.8	3.4	—	—	—	—
3. Fan								
Number of fan stages	2	2	2	1	1	1	1	1
Fan diameter, cm	102.87	102.87	127.51	124.97	180.34	180.34	173.48	186.69
Fan rotational speed, rev/min	8005	8420	6320	7290	3066 ^b	3712 ^b	4705	4499
Fan tip speed, m/s	431.2	453.5	421.9	477.0	289.5	350.5	427.4	439.8
Fan-tip-section pressure ratio	1.97	2.06	1.82	1.76	1.27	1.33	1.51	1.66
Number of fan blades	27/40	27/40	35/32	34	18 ^e	28 ^h	44	33
Number of fan-stator outlet guide vanes	56	56	38	84	33	33	83	70
Ratio of number of fan outlet guide vanes to number of fan blades	2.07/	2.07/	1.09/	2.47	1.83	1.18	1.89	2.12
1.40	1.40	1.40	1.19					
Spacing between tip of fan outlet vanes and fan blades : average fan-blade chord ^a	0.8/1.7	0.8/1.7	0.9/1.3	3.3	2.5	2.8	2.5	3.8
Spacing between root of fan outlet vanes and fan blades : average fan-blade chord ^a	0.4/0.5	0.4/0.5	0.8/1.2	3.1	2.3	2.4	2.3	2.3
Fan-blade-passage frequency, Hz	3602/	3789/	3687/	4131	920	1732	3450	2474
5337								
4. Acoustical treatment								
Fan-case (fan-frame) acoustical treatment: (yes or no)	—	—	—	Yes	Yes	Yes	Yes	—
-on outer wall forward of fan rotor blades	No	No	No	Yes	Yes	Yes	Yes	No
-on outer wall between fan rotor blades and outlet guide vanes	No	No	No	No	Yes	Yes	No	No
-on inner wall of fan-exhaust duct between fan blades and fan outlet guide vanes	No	No	No	No	Yes	Yes	No	No
-on fan-stator outlet guide vanes	No	No	No	No	Yes	Yes	No	No
Number of last-stage low-pressure-turbine rotor blades	74	74	80	58	100	100	160	64
Number of last-stage low-pressure-turbine outlet-support struts	4	4	4	8	14	14	12	12
Ratio of number of outlet support struts to number of last-stage LP turbine blades	0.054	0.054	0.050	0.138	0.140	0.140	0.075	0.188
Spacing between tip of last LP turbine blades and outlet struts : aver. last LP turbine blade chord ^a	4.0	4.0	2.5	2.2	0.86 ^f	0.86 ^f	2.6	0.82
If geared fan, turbine shaft speed, rev/min	—	—	—	—	4535	4592	—	—
LP turbine-blade-passage frequency, Hz	9873	10,385	8427	7047	7558	7653	12,547	4799
6. Jet								
Fan-discharge jet velocity, m/s	538 ^c	592 ^c	320	393 ^d	204	216 ^g	274	298
Turbine-discharge jet velocity, m/s	—	—	494	—	245	322 ^g	403	421

^aSpacing and chord lengths are measured in a plane containing the engine axis and along lines parallel to the engine centerline. Average blade chord is determined by averaging severa: projected axial chord lengths between the root and the tip of a blade. Spacing between the tip or root of an outlet stator vane and a rotor blade is measured from the projected leading edge of a vane to the projected trailing edge of a blade.

^bGeared fan

^cRound, internal nozzle on the turbine discharge; long fan duct; single, common-flow, round, external exhaust nozzle

^dMechanical, forced-mixing internal nozzle on the turbine discharge; long fan duct; single, common-flow, round, external exhaust nozzle

^eVariable-pitch fan blades

^fOutlet struts slant aft at the root to a spacing ratio of 0.14

^g917-percent mixed flow from the single, D-shaped, external exhaust nozzle

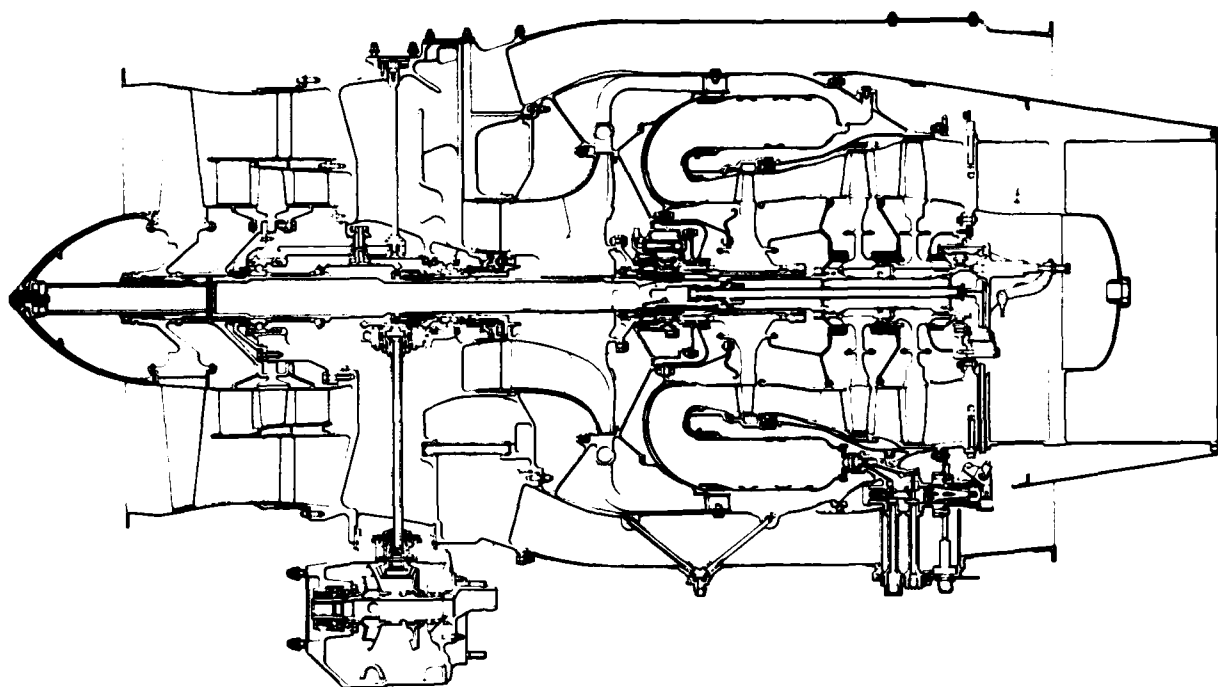
^hFixed-pitch fan blades

ⁱReal (non-ideal) exhaust nozzles

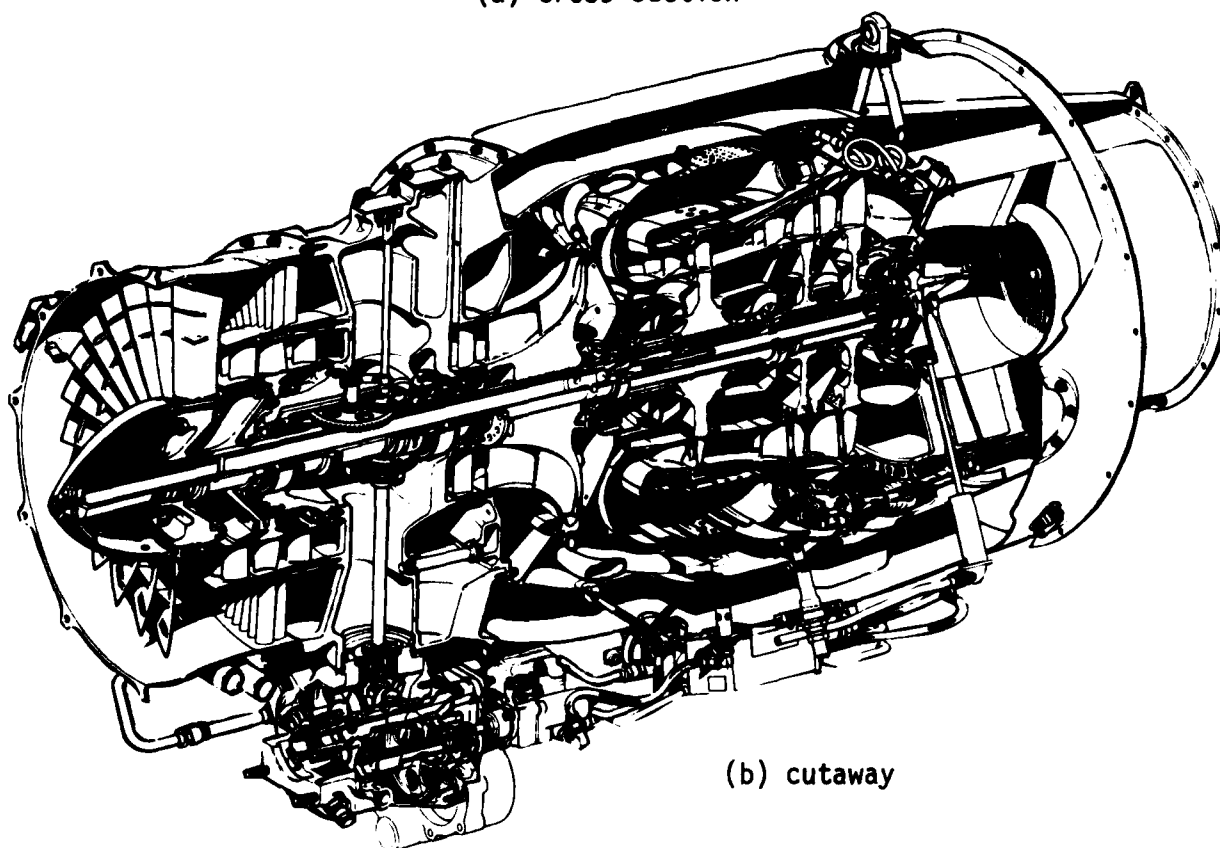
Table 4 . Concluded
(c) HIGH-THRUST ENGINES FOR CIVIL JET TRANSPORTS

PARAMETER	CF6-80	RB. 211 -228	JT8D-7A	RB. 211 -524B	CF6-50C/50E	JT9D- 50A/70A
1. General						
Year certified or delivered	1970	1972	1972	1976	1973	1974
Total thrust, kN	177.93	186.82	205.73	222.41	233.53	235.76
Total mass flow rate (air + fuel), kg/s	592.9	625.1	700.8	689.0	673.1	743.9
Bypass ratio	5.88	4.62	5.1	4.41	4.2	4.9
Fan-exit mass flow rate (air), kg/s	506.7	513.0	586.0	561.6	543.7	617.8
Core-engine mass flow rate (air + fuel), kg/s	86.2	111.1	114.8	127.4	129.4	126.1
2. Inlet Guide Vanes (IGV)						
Inlet guide vanes or support struts?	No	No	No	No	No	No
Spacing between tip of IGVs (or struts) and fan blades : average fan-blade chord ^a	—	—	—	—	—	—
3. Fan						
Number of fan stages	1	1	1	1	1	1
Fan diameter, cm	219.46	217.17	234.44	217.17	219.46	237.74
Fan rotational speed, rev/min	3425	3613	3310	3809	3833	3440
Fan tip speed, m/s	393.6	410.8	406.3	433.1	440.4	428.2
Fan-tip-section pressure ratio	1.64	1.54	1.50	1.65	1.75	1.60
Number of fan blades	38	33	46	33	38	46
Number of fan-stator outlet guide vanes	80	70	108	70	80	96
Ratio of number of fan outlet guide vanes to number of fan blades	2.11	2.12	2.35	2.12	2.11	2.09
Spacing between tip of fan outlet vanes and fan blades : average fan-blade chord ^a	2.1	3.2	3.3	3.0	2.1	4.6
Spacing between root of fan outlet vanes and fan blades : average fan-blade chord ^a	1.2	2.0	1.7	1.8	1.2	2.8
Fan-blade-passageway frequency, Hz	2169	1987	2538	2095	2428	2637
4. Acoustical treatment						
Fan-case (fan-frame) acoustical treatment: (yes or no)	Yes	—	—	—	Yes	—
-on outer wall forward of fan rotor blades	Yes	Yes	Yes	Yes	Yes	Yes
-on outer wall between fan rotor blades and outlet guide vanes	Yes	No	No	No	Yes	No
-on inner wall of fan-exhaust duct between fan blades and fan outlet guide vanes	No	No	No	No	No	No
-on fan-stator outlet guide vanes	No	No	No	No	No	No
5. Low-Pressure (LP) turbine						
Number of last-stage low-pressure-turbine rotor blades	90	72	102	72	86	102
Number of last-stage low-pressure-turbine outlet-support struts	8	18	15	18	8	15
Ratio of number of outlet support struts to number of last-stage LP turbine blades	0.089	0.250	0.147	0.250	0.093	0.147
Spacing between tip of last LP turbine blades and outlet struts : aver. last LP turbine blade chord ^a	1.6	0.86	2.4	0.86	1.8	2.1
If geared fan, turbine shaft speed, rev/min	—	—	—	—	—	—
LP turbine-blade-passageway frequency, Hz	5138	4336	5627	4571	5494	5848
6. Jet						
Fan-discharge jet velocity, m/s	287	270	263	294	318	290
Turbine-discharge jet velocity, m/s	415	396	392	423	480	475

^a Spacing and chord lengths are measured in a plane containing the engine axis and along lines parallel to the engine centerline. Average blade chord is determined by averaging several projected axial chord lengths between the root and the tip of a blade. Spacing between the tip or root of an outlet stator vane and a rotor blade is measured from the projected leading edge of a vane to the projected trailing edge of a blade.



(a) cross section



(b) cutaway

Figure 1. JT15D-4 from Pratt & Whitney Aircraft of Canada Ltd.

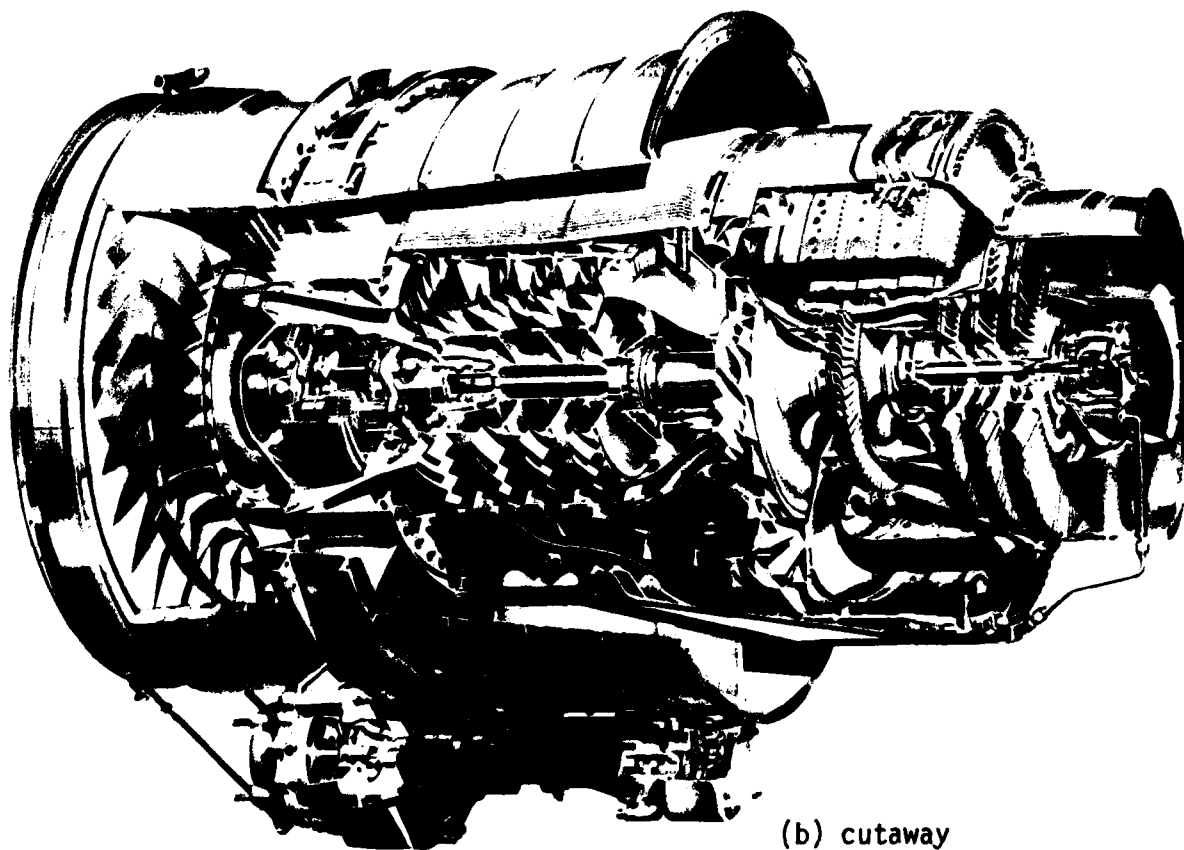
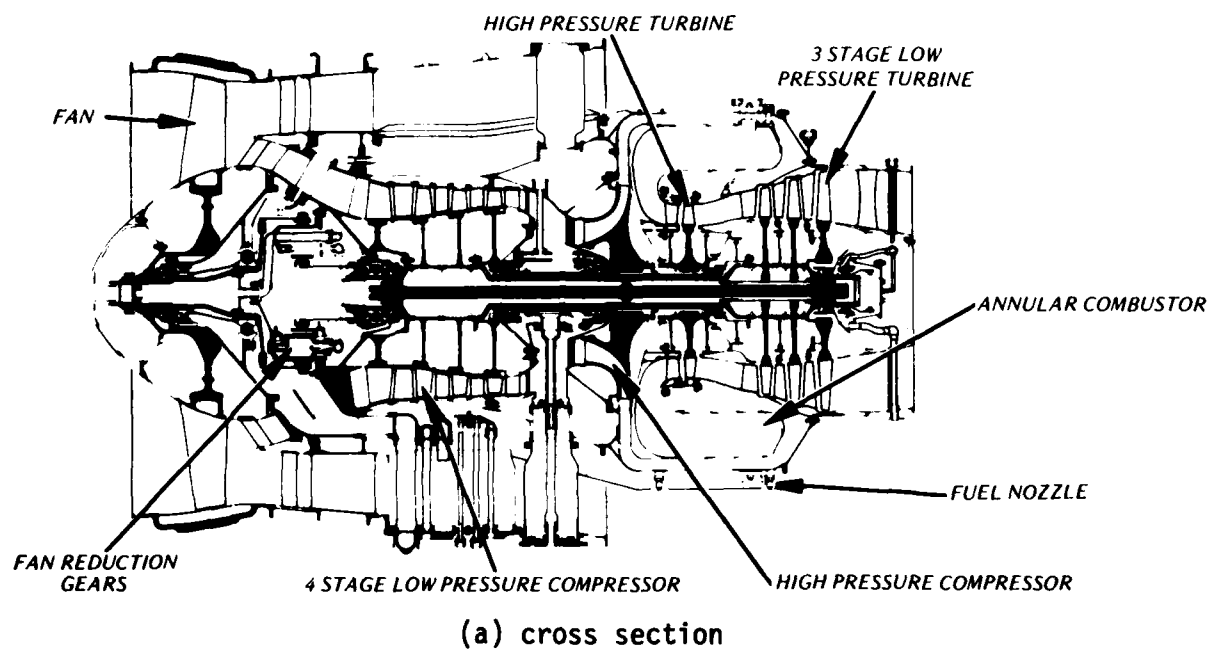


Figure 2. TFE731 from Garrett Turbine Engine Company

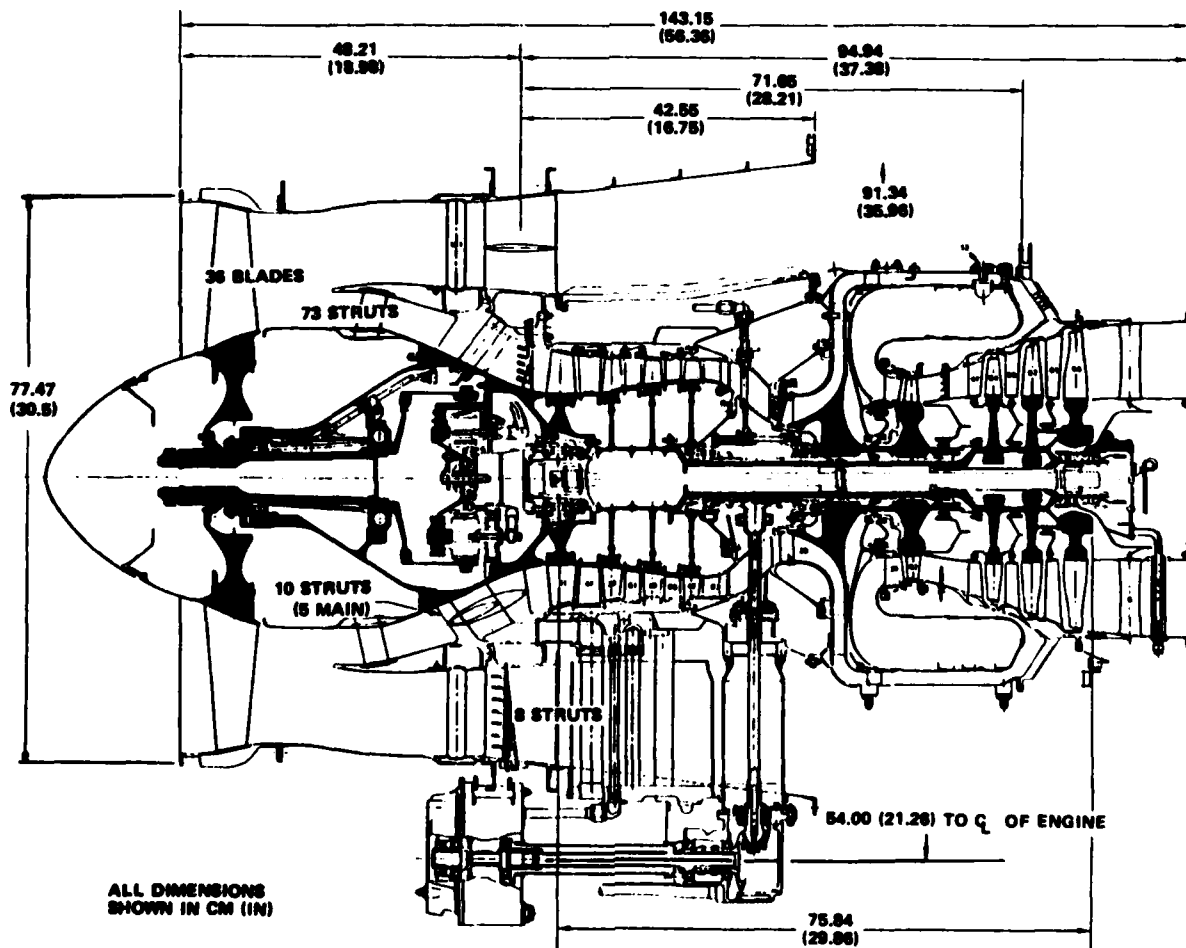
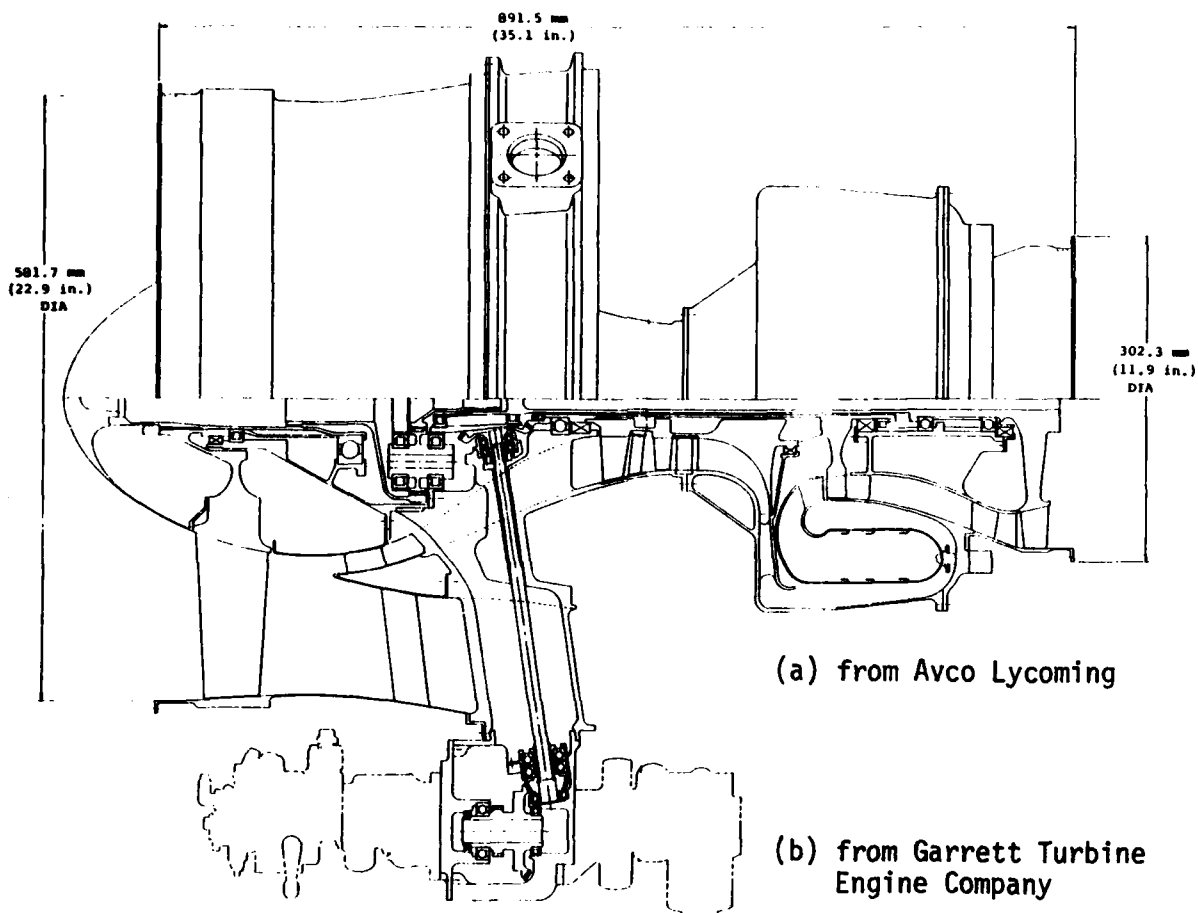
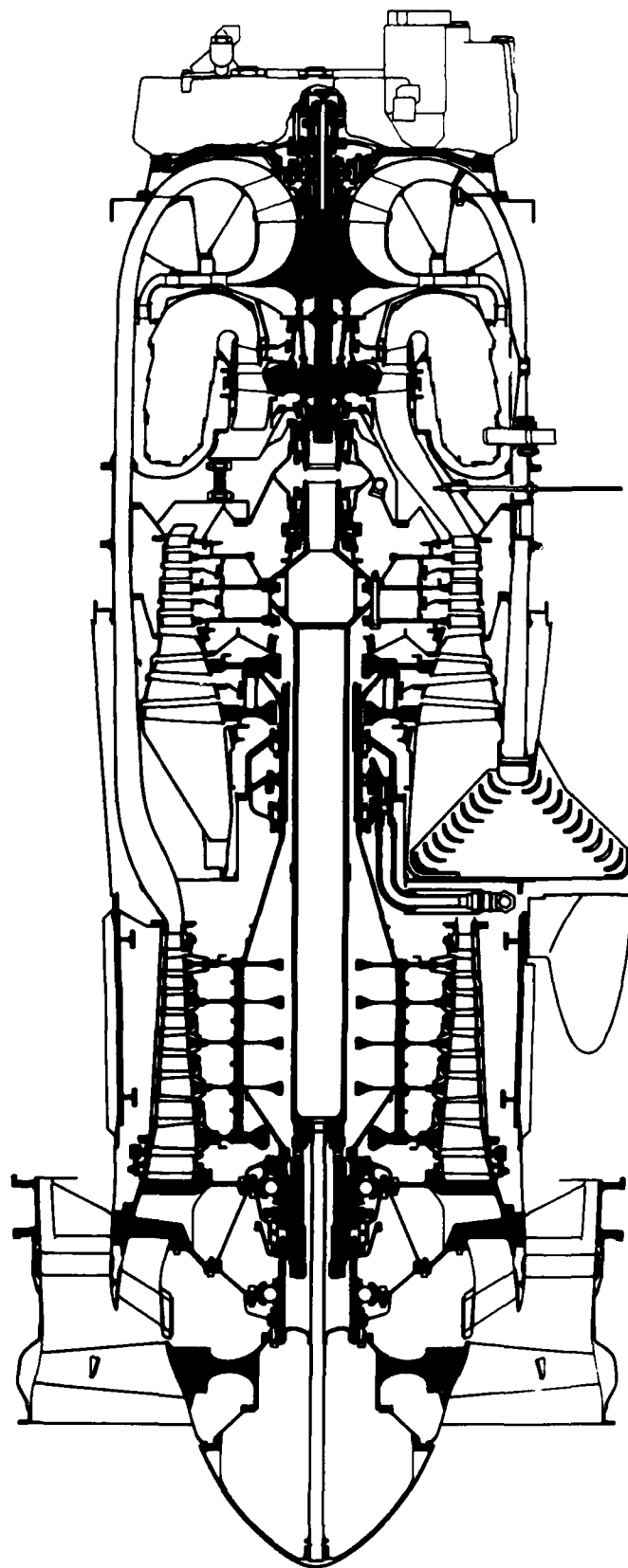


Figure 3. NASA QCGAT (Quiet, Clean General-Aviation Turbofan)



(a) cross section

Figure 4. ATF3-6 from Garrett Turbine Engine Company

- | | | | | | |
|-----|--------------------------------|-----|-------------------------------------|------|-------------------------|
| 1. | SINGLE STAGE FAN | 22. | SINGLE-STAGE HP AXIAL TURBINE WHEEL | 44. | OIL PUMP AND |
| 2. | COMPRESSOR | 23. | AXIAL COOLED TURBINE BLADES | 45. | ON PUMP DRIVE |
| 3. | OIL COOLER | 24. | HP SHAFT COUPLING | 46. | AT FINE SHUT |
| 4. | INLET STATOR (VARIABLE) | 25. | HP SHAFT CURVING COUPLING | 47. | MD FINE SHUT |
| 5. | FAN SPINNING COMPRESSOR | 26. | HP SHAFT SPLITTER | 48. | FORWARD FINE-SHIELD |
| 6. | FAN SPINNING COMPRESSOR | 27. | HP TURBINE STATOR | 49. | FORWARD FINE-SHIELD |
| 7. | 5 STAGE LP AXIAL COMPRESSOR | 28. | 2-STAGE LP TURBINE | 50. | HP FLYING |
| 8. | ALUMINUM-CLAD COMPRESSOR FIXED | 29. | HP SPOOL REAR HOLLER BEARING | 51. | HP CASCADE DAMPER |
| 9. | STATOR RING - ALL STAGES | 30. | 3-STAGE FAN TURBINE | 52. | FORWARD FRAME AND MOUNT |
| 10. | FAN SHAFT THRUST BEARING | 31. | HP TURBINE TRANSDUCER GEAR | 53. | FORWARD FRAME AND MOUNT |
| 11. | HP SHAFT FRONT ROLLER BEARING | 32. | HP CASE | 54. | HP TURBINE STATOR |
| 12. | HP COMPRESSOR FACE SHROUD | 33. | HP TURBINE DRIVE COUPLING SHAFT | 55. | HP TURBINE STATOR |
| 13. | HP CENTRIFUGAL COMPRESSOR | 34. | HP TURBINE DRIVE COUPLING SHAFT | 56. | HP TURBINE STATOR |
| 14. | FAN SPOOL ROLLER BEARING | 35. | HP TURBINE DRIVE COUPLING SHAFT | 57. | HP TURBINE STATOR |
| 15. | FAN SPOOL ROLLER BEARING | 36. | HP TURBINE DRIVE COUPLING SHAFT | 58. | HP TURBINE STATOR |
| 16. | FAN SPOOL ROLLER BEARING | 37. | HP TURBINE DRIVE COUPLING SHAFT | 59. | HP TURBINE STATOR |
| 17. | 3-STAGE FAN TURBINE | 38. | HP TURBINE DRIVE COUPLING SHAFT | 60. | HP TURBINE STATOR |
| 18. | 3-STAGE FAN TURBINE | 39. | HP TURBINE DRIVE COUPLING SHAFT | 61. | HP TURBINE STATOR |
| 19. | FUEL MANIFOLD | 40. | HP TURBINE DRIVE COUPLING SHAFT | 62. | HP TURBINE STATOR |
| 20. | FUEL MANIFOLD | 41. | HP TURBINE DRIVE COUPLING SHAFT | 63. | HP TURBINE STATOR |
| 21. | HP TURBINE STATOR | 42. | HP TURBINE DRIVE COUPLING SHAFT | 64. | HP TURBINE STATOR |
| | | 43. | HP TURBINE DRIVE COUPLING SHAFT | 65. | HP TURBINE STATOR |
| | | 44. | HP TURBINE DRIVE COUPLING SHAFT | 66. | HP TURBINE STATOR |
| | | 45. | HP TURBINE DRIVE COUPLING SHAFT | 67. | HP TURBINE STATOR |
| | | 46. | HP TURBINE DRIVE COUPLING SHAFT | 68. | HP TURBINE STATOR |
| | | 47. | HP TURBINE DRIVE COUPLING SHAFT | 69. | HP TURBINE STATOR |
| | | 48. | HP TURBINE DRIVE COUPLING SHAFT | 70. | HP TURBINE STATOR |
| | | 49. | HP TURBINE DRIVE COUPLING SHAFT | 71. | HP TURBINE STATOR |
| | | 50. | HP TURBINE DRIVE COUPLING SHAFT | 72. | HP TURBINE STATOR |
| | | 51. | HP TURBINE DRIVE COUPLING SHAFT | 73. | HP TURBINE STATOR |
| | | 52. | HP TURBINE DRIVE COUPLING SHAFT | 74. | HP TURBINE STATOR |
| | | 53. | HP TURBINE DRIVE COUPLING SHAFT | 75. | HP TURBINE STATOR |
| | | 54. | HP TURBINE DRIVE COUPLING SHAFT | 76. | HP TURBINE STATOR |
| | | 55. | HP TURBINE DRIVE COUPLING SHAFT | 77. | HP TURBINE STATOR |
| | | 56. | HP TURBINE DRIVE COUPLING SHAFT | 78. | HP TURBINE STATOR |
| | | 57. | HP TURBINE DRIVE COUPLING SHAFT | 79. | HP TURBINE STATOR |
| | | 58. | HP TURBINE DRIVE COUPLING SHAFT | 80. | HP TURBINE STATOR |
| | | 59. | HP TURBINE DRIVE COUPLING SHAFT | 81. | HP TURBINE STATOR |
| | | 60. | HP TURBINE DRIVE COUPLING SHAFT | 82. | HP TURBINE STATOR |
| | | 61. | HP TURBINE DRIVE COUPLING SHAFT | 83. | HP TURBINE STATOR |
| | | 62. | HP TURBINE DRIVE COUPLING SHAFT | 84. | HP TURBINE STATOR |
| | | 63. | HP TURBINE DRIVE COUPLING SHAFT | 85. | HP TURBINE STATOR |
| | | 64. | HP TURBINE DRIVE COUPLING SHAFT | 86. | HP TURBINE STATOR |
| | | 65. | HP TURBINE DRIVE COUPLING SHAFT | 87. | HP TURBINE STATOR |
| | | 66. | HP TURBINE DRIVE COUPLING SHAFT | 88. | HP TURBINE STATOR |
| | | 67. | HP TURBINE DRIVE COUPLING SHAFT | 89. | HP TURBINE STATOR |
| | | 68. | HP TURBINE DRIVE COUPLING SHAFT | 90. | HP TURBINE STATOR |
| | | 69. | HP TURBINE DRIVE COUPLING SHAFT | 91. | HP TURBINE STATOR |
| | | 70. | HP TURBINE DRIVE COUPLING SHAFT | 92. | HP TURBINE STATOR |
| | | 71. | HP TURBINE DRIVE COUPLING SHAFT | 93. | HP TURBINE STATOR |
| | | 72. | HP TURBINE DRIVE COUPLING SHAFT | 94. | HP TURBINE STATOR |
| | | 73. | HP TURBINE DRIVE COUPLING SHAFT | 95. | HP TURBINE STATOR |
| | | 74. | HP TURBINE DRIVE COUPLING SHAFT | 96. | HP TURBINE STATOR |
| | | 75. | HP TURBINE DRIVE COUPLING SHAFT | 97. | HP TURBINE STATOR |
| | | 76. | HP TURBINE DRIVE COUPLING SHAFT | 98. | HP TURBINE STATOR |
| | | 77. | HP TURBINE DRIVE COUPLING SHAFT | 99. | HP TURBINE STATOR |
| | | 78. | HP TURBINE DRIVE COUPLING SHAFT | 100. | HP TURBINE STATOR |

(b) cutaway

Figure 4. Concluded

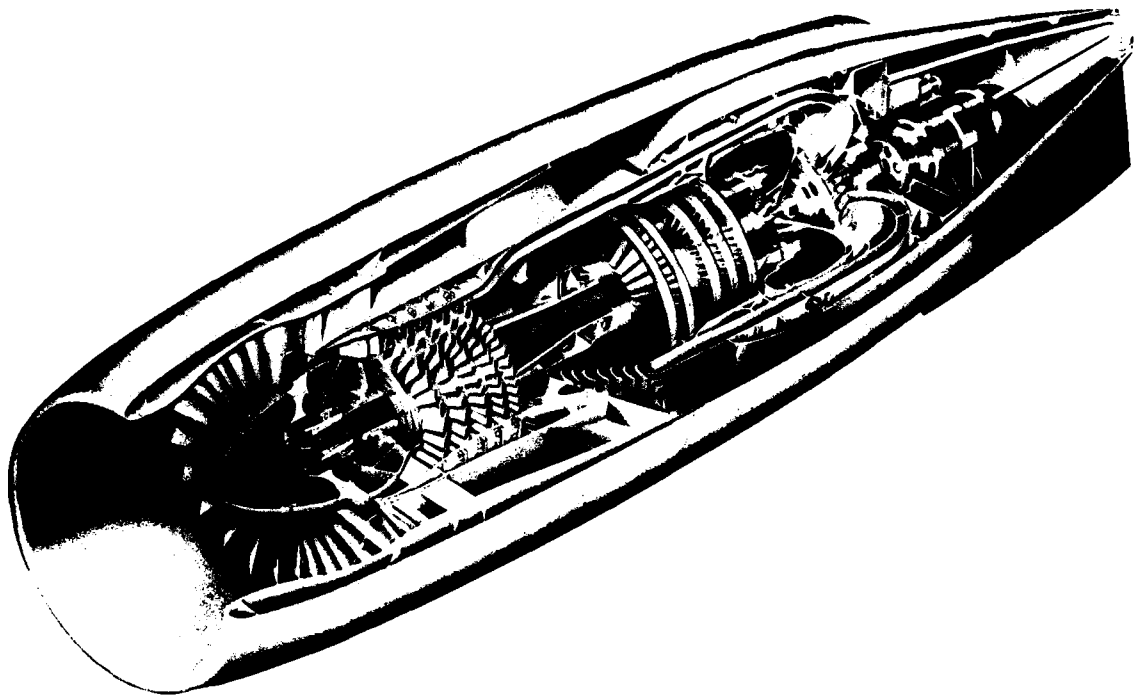


Figure 5. Cutaway view of ATF3-6 installed in a nacelle

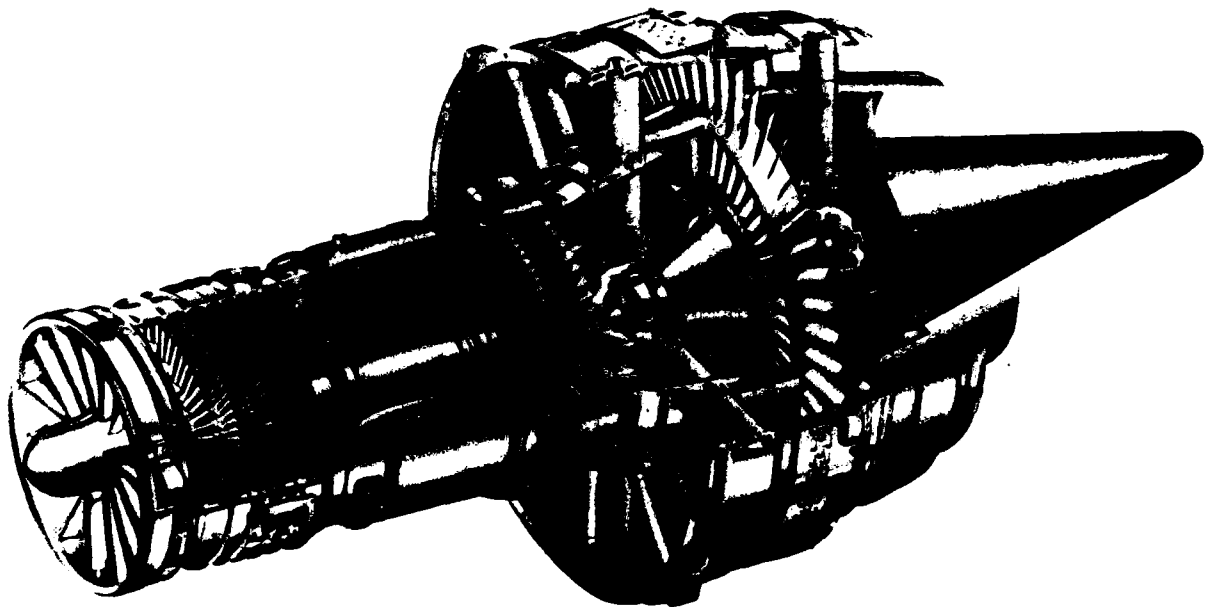


Figure 6. CF700 from General Electric

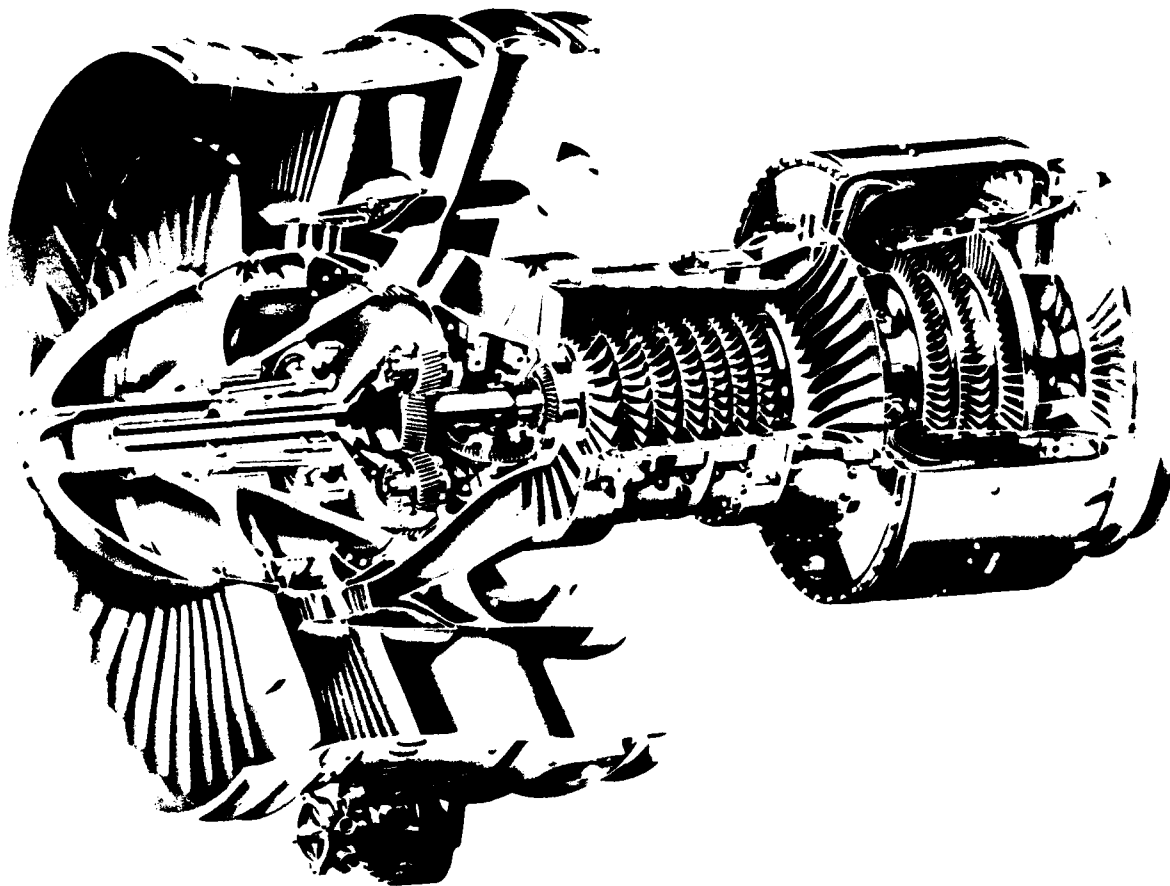


Figure 7. ALF-502 from Avco Lycoming

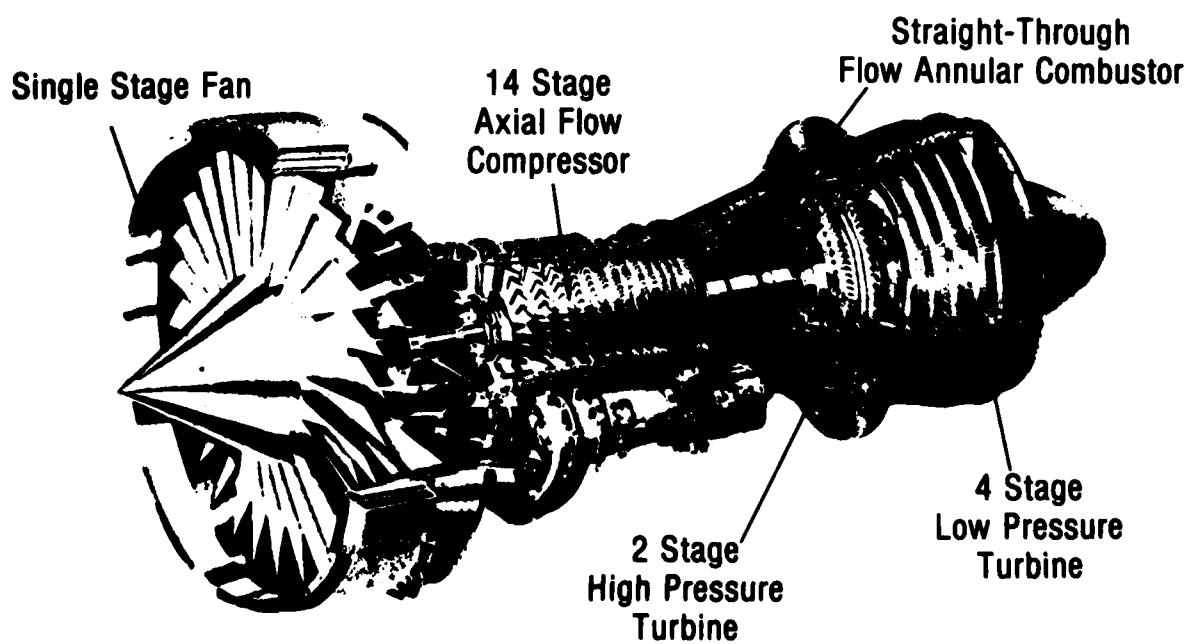
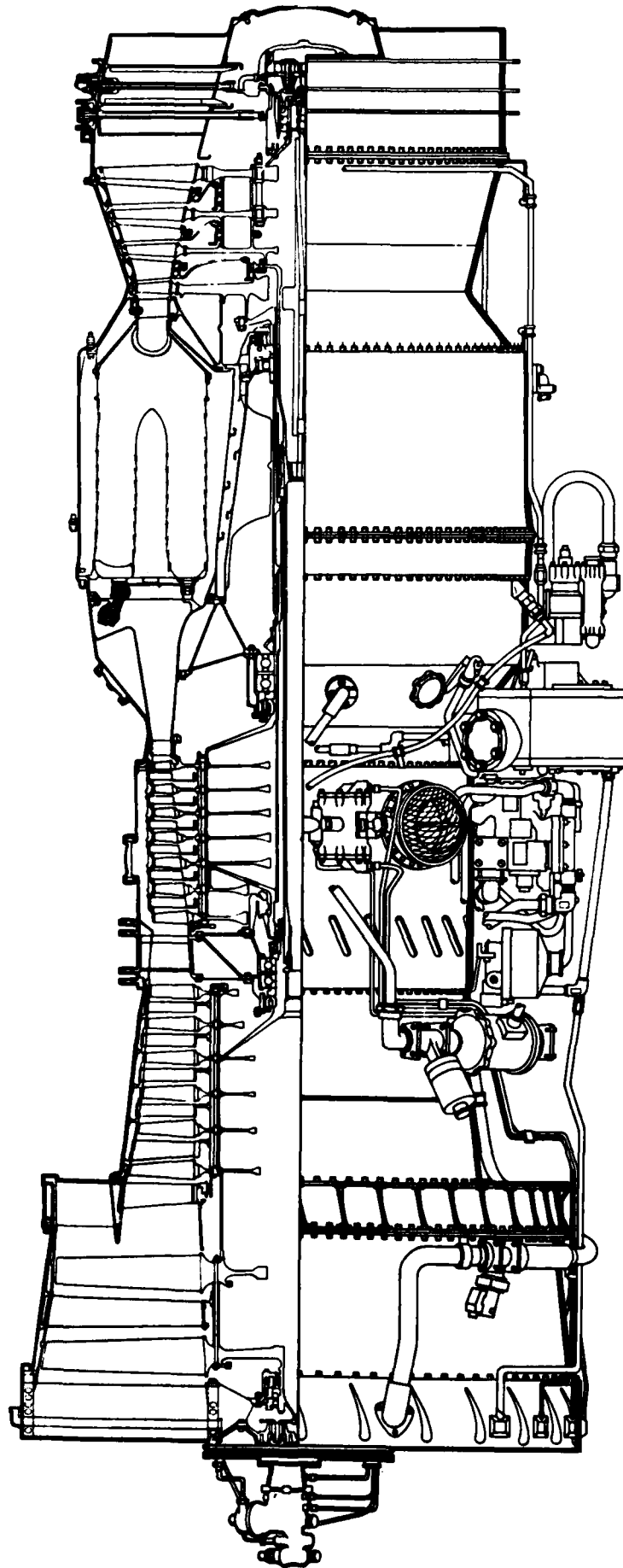
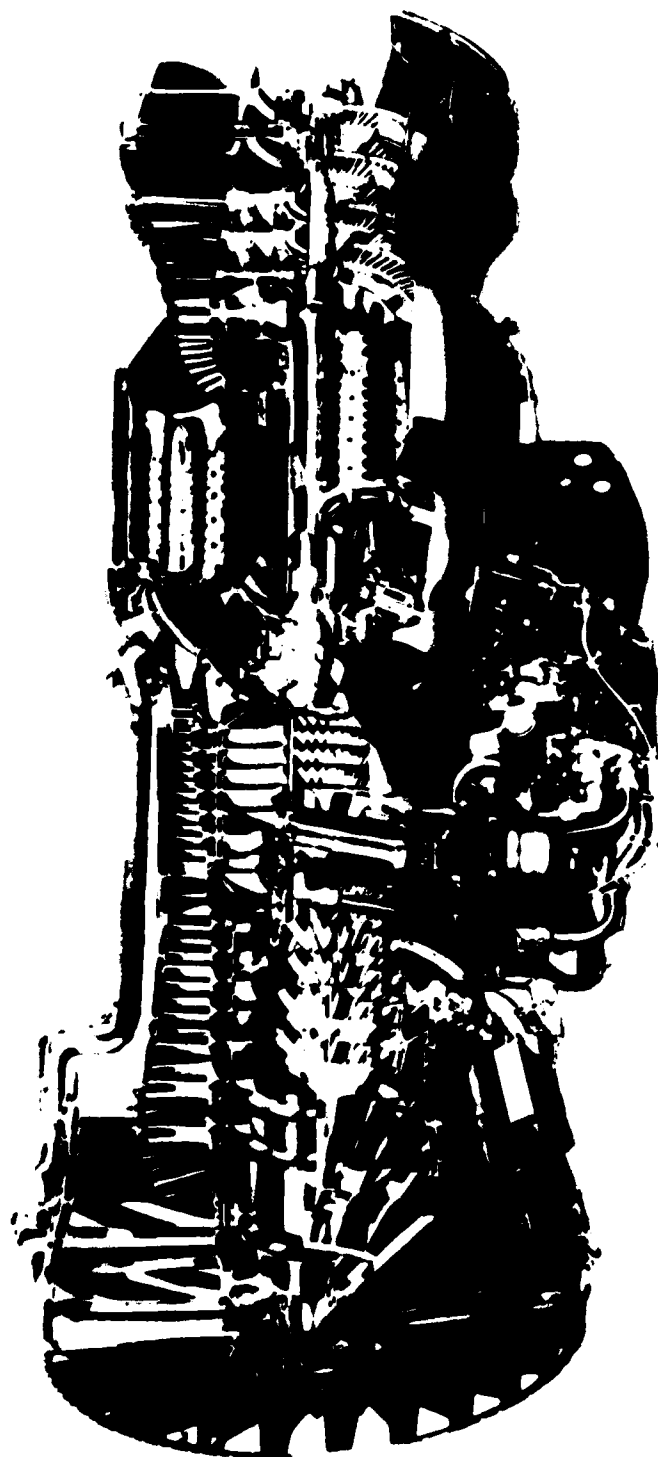


Figure 8. CF34 from General Electric



(a) cross section

Figure 9. JT3D from Pratt & Whitney Aircraft



(b) cutaway

Figure 9. Concluded

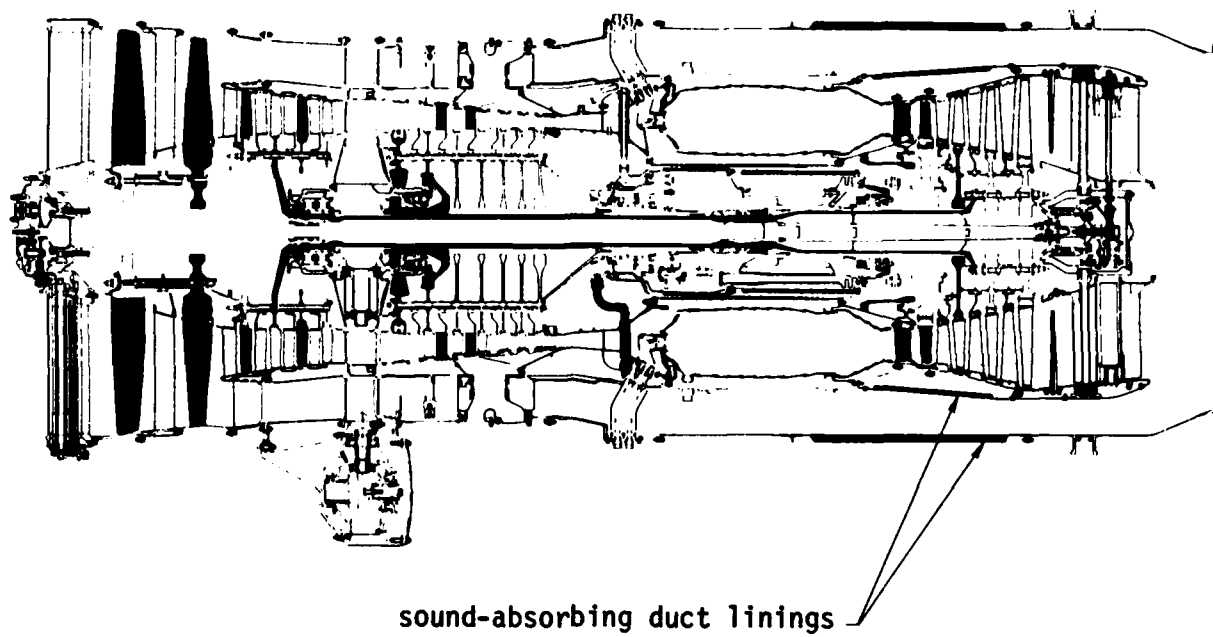


Figure 10. JT8D from Pratt & Whitney Aircraft

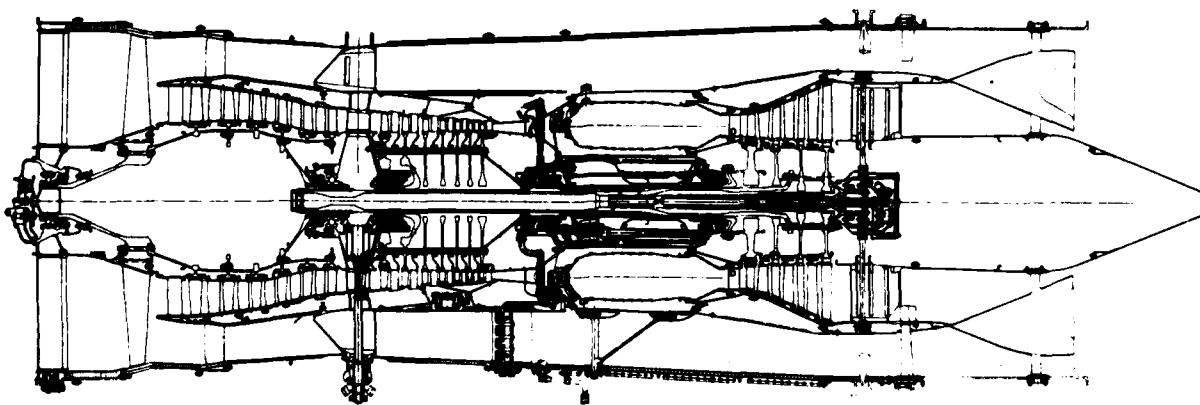
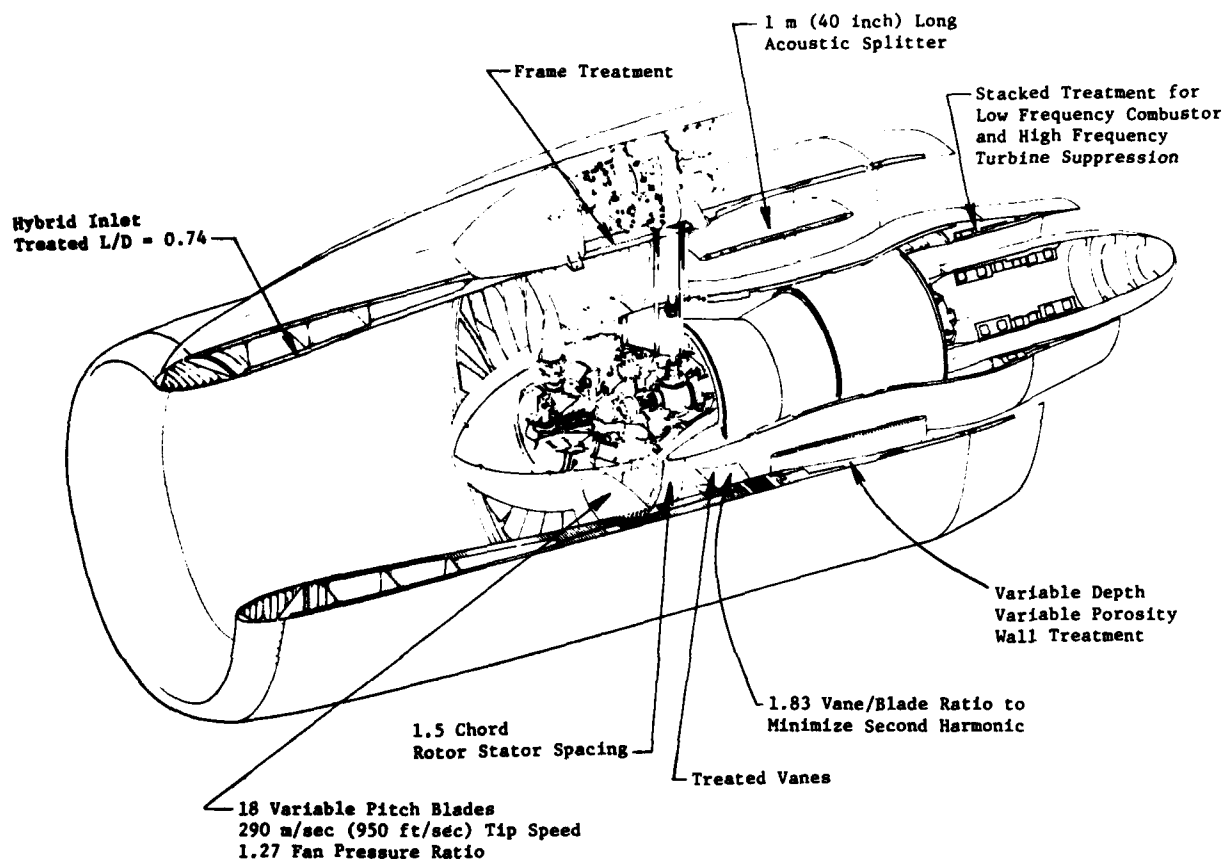
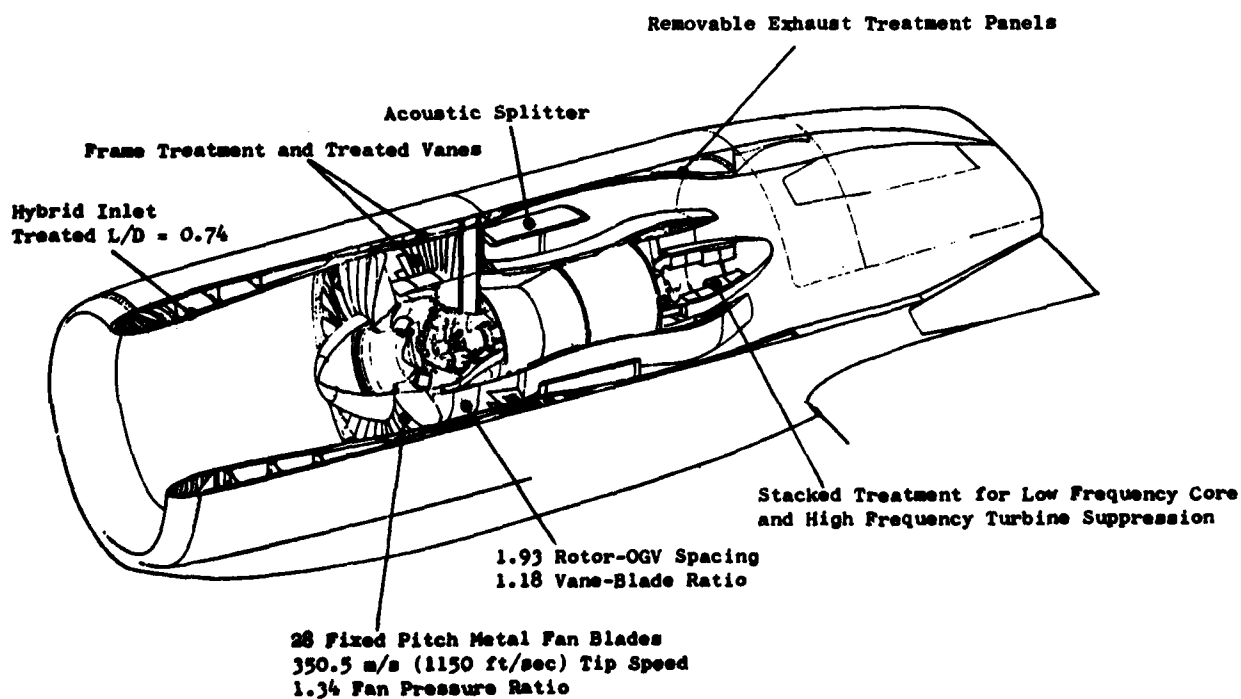


Figure 11. JT8D-209 from Pratt & Whitney Aircraft



(a) under-the-wing for lower-surface-blown flaps



(b) over-the-wing for upper-surface-blown flaps

Figure 12. NASA QCSEE (Quiet, Clean, Short-Haul Experimental Engine)

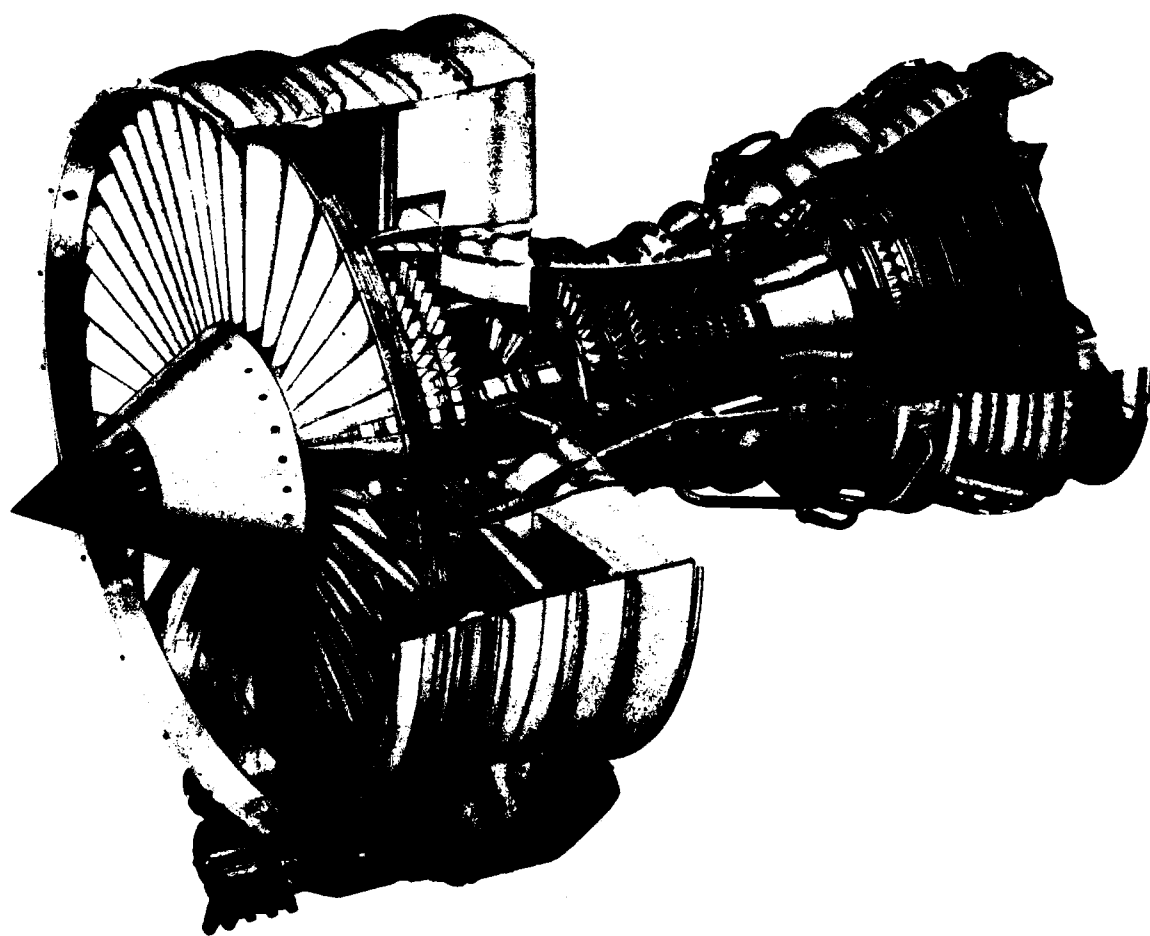


Figure 13. CFM56 from General Electric and SNECMA

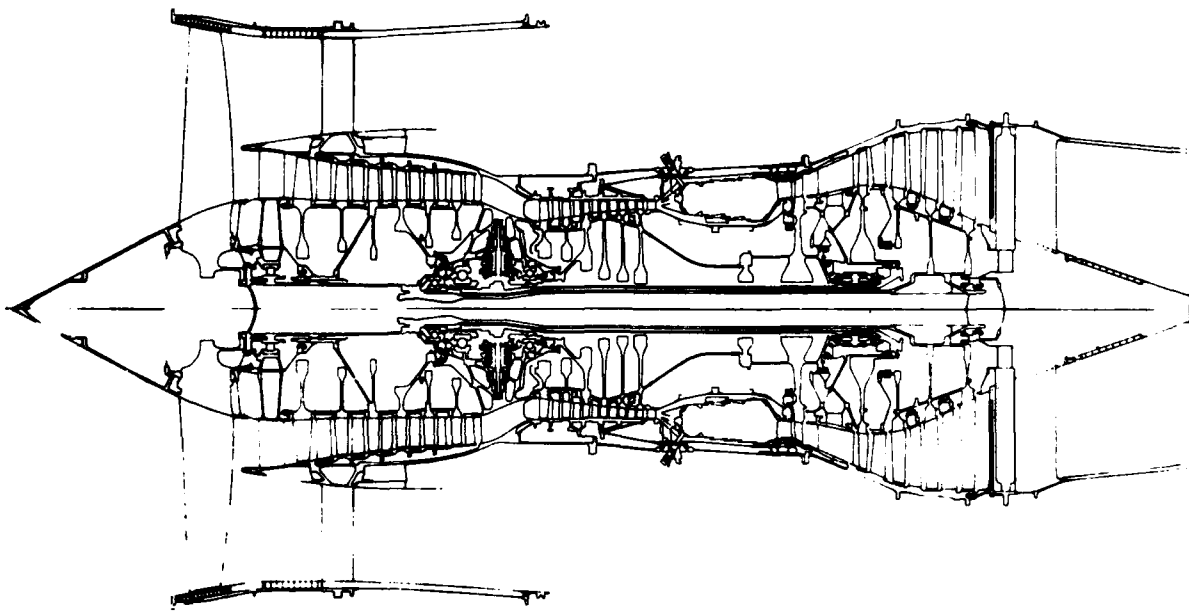


Figure 14. RB.211-535 from Rolls Royce

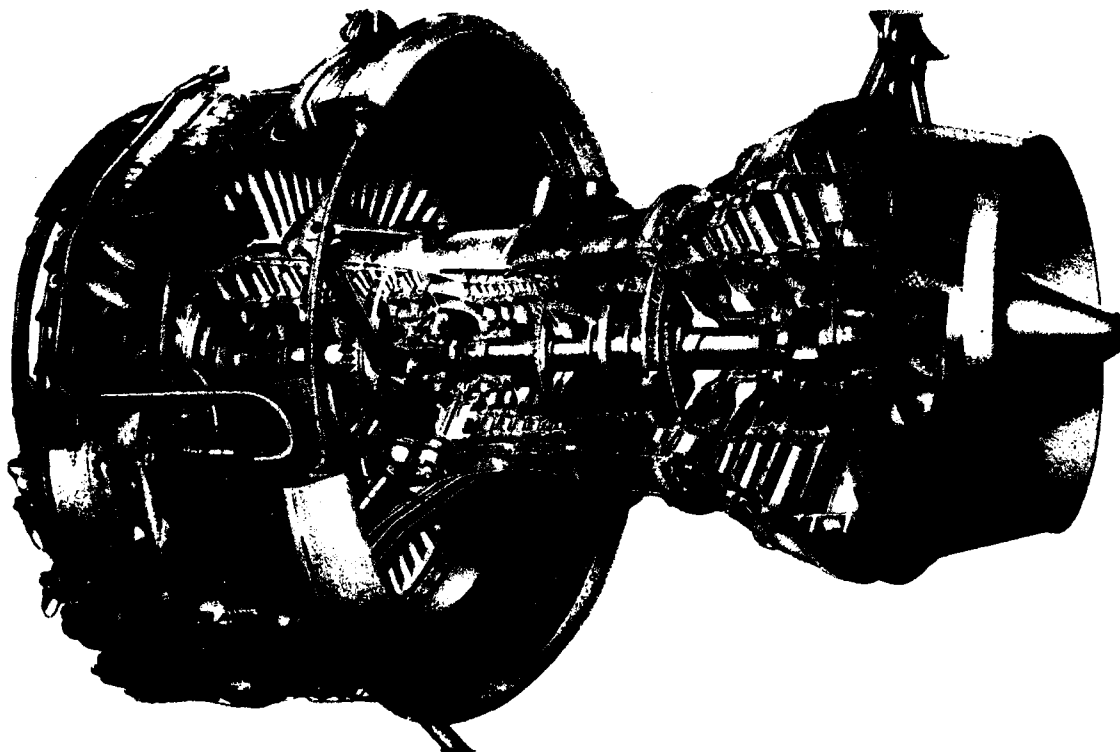


Figure 15. RB.211-22 from Rolls Royce

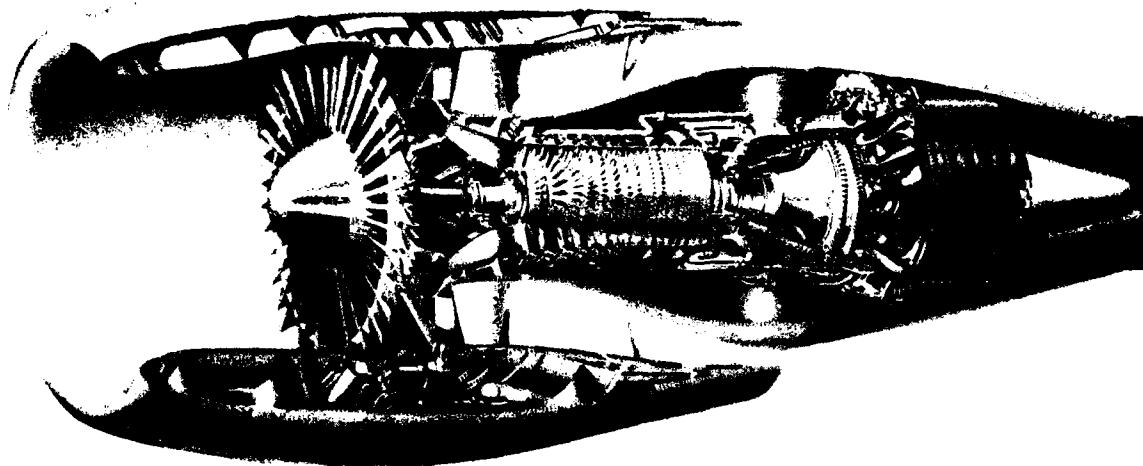


Figure 16. CF6-6 from General Electric

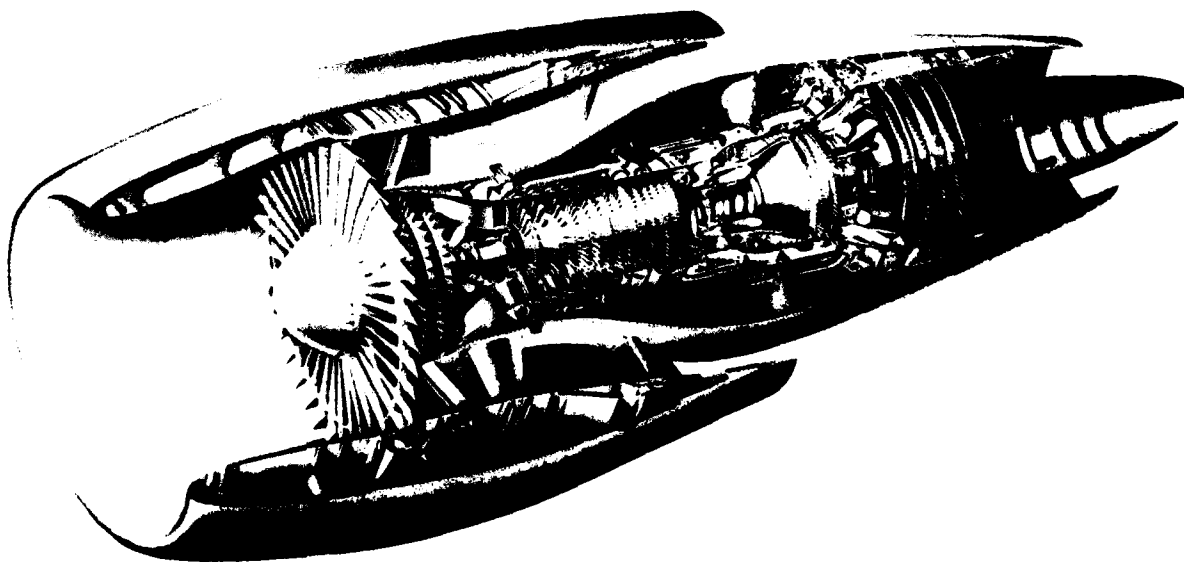
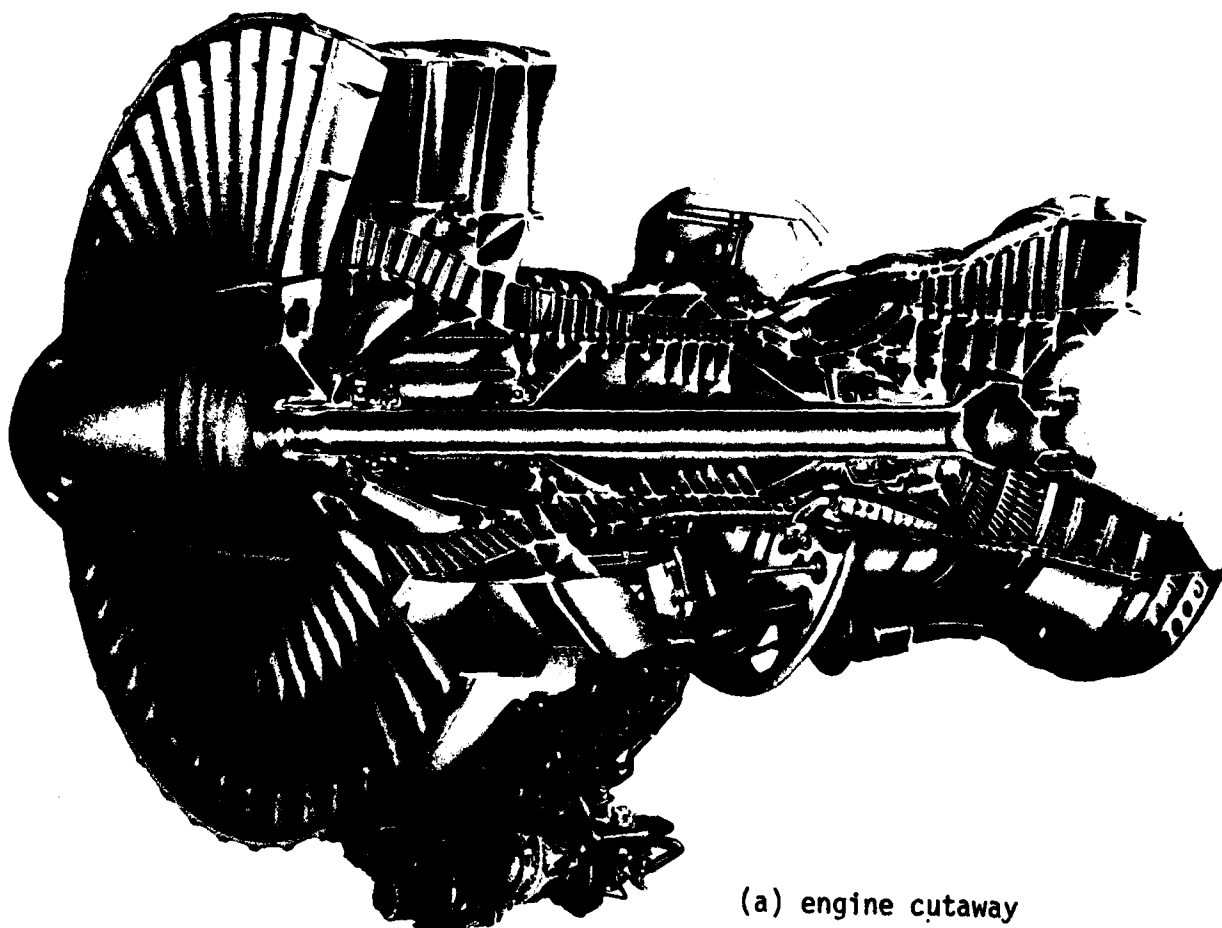
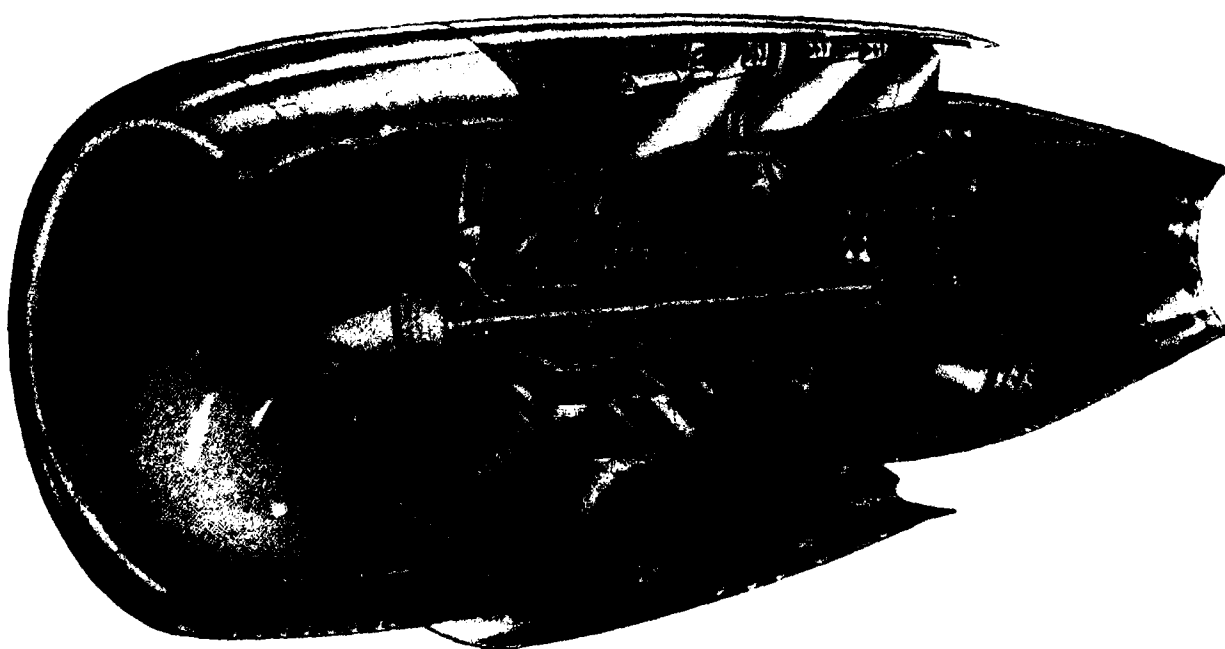


Figure 17. CF6-50 from General Electric

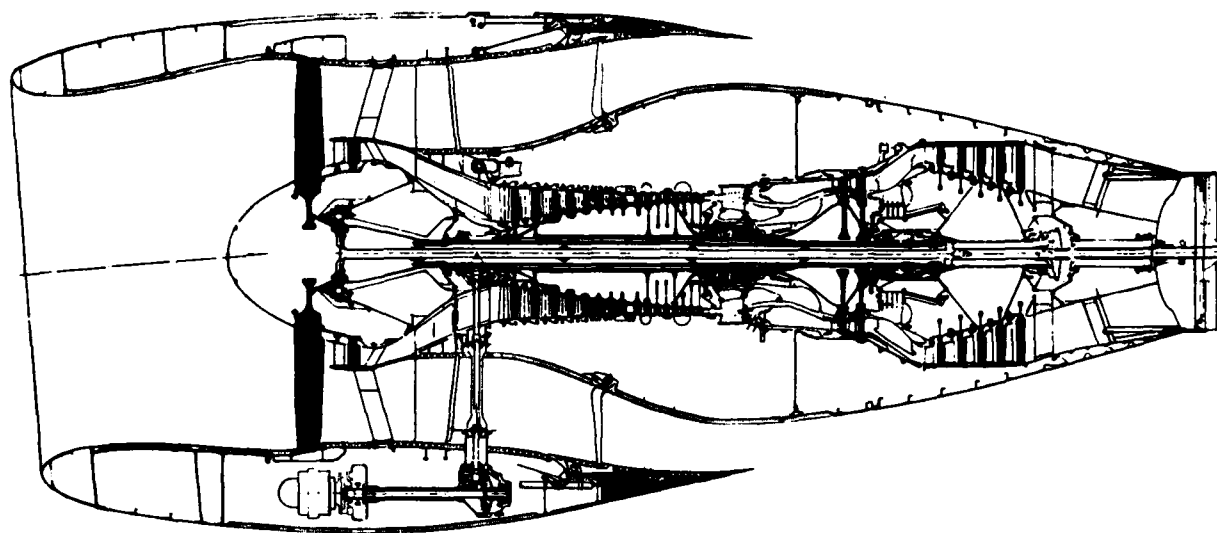


(a) engine cutaway

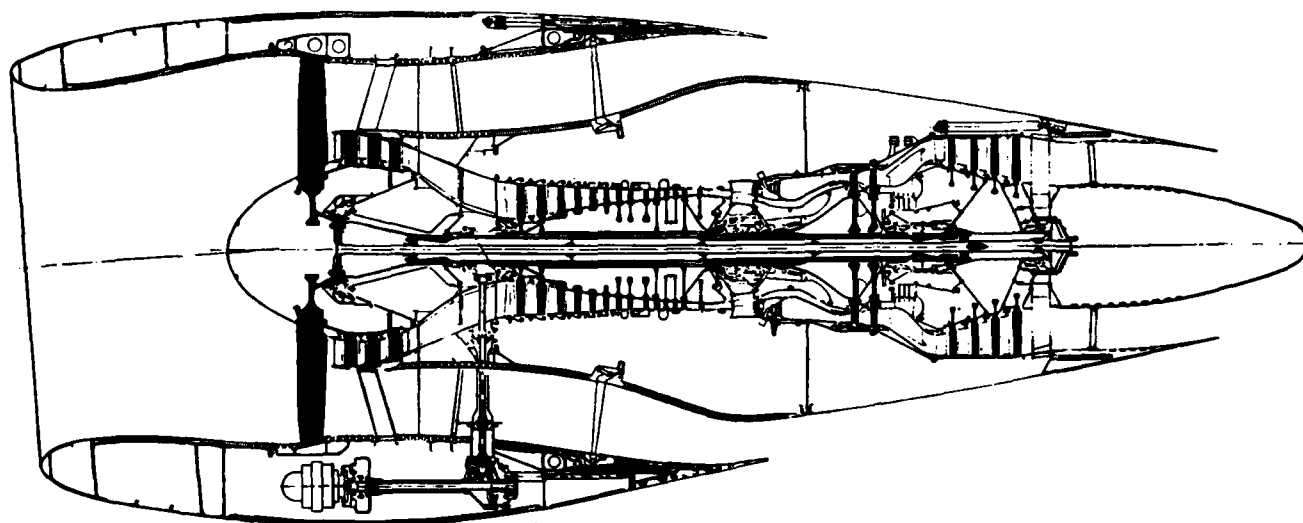


(b) cutaway of installation in a nacelle

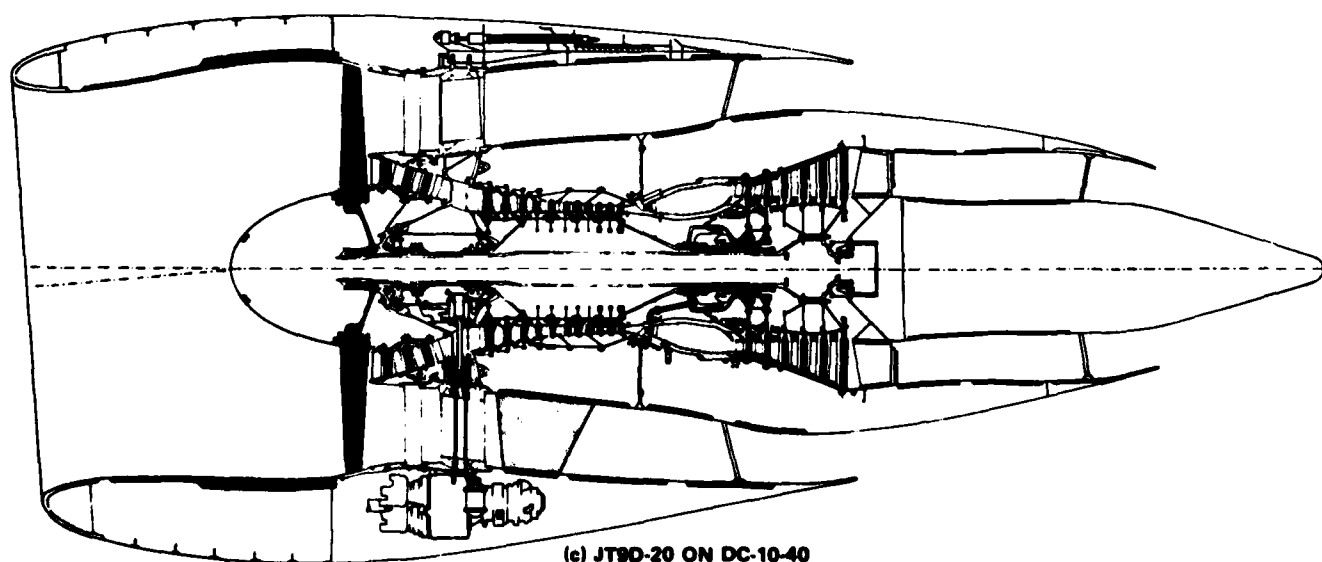
Figure 18. JT9D-59A, -70A from Pratt & Whitney Aircraft



(a) CF6-6D ON DC-10-10



(b) CF6-50A ON DC-10-30



(c) JT9D-20 ON DC-10-40

Figure 19. Cross-section views of engine installations in wing-engine nacelles on DC-10 airplanes

